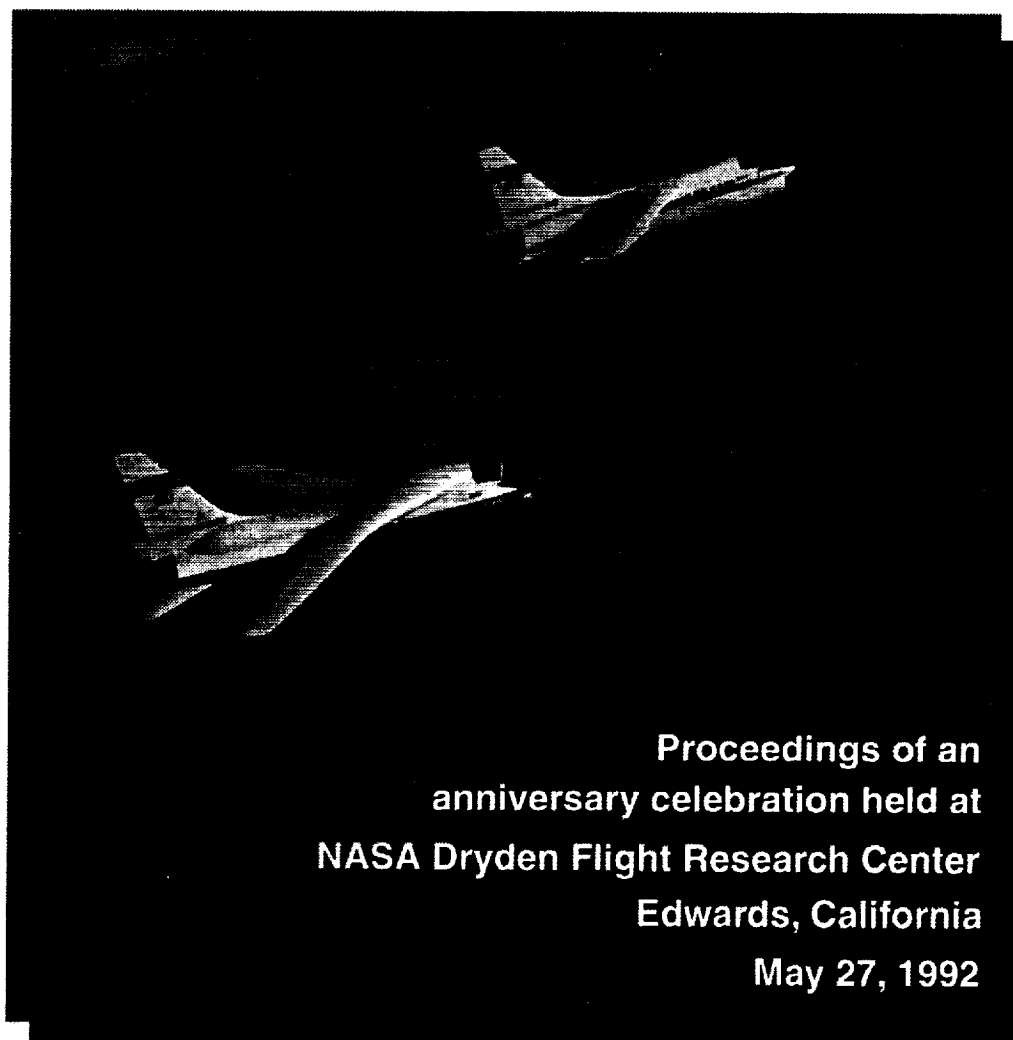


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Volume I

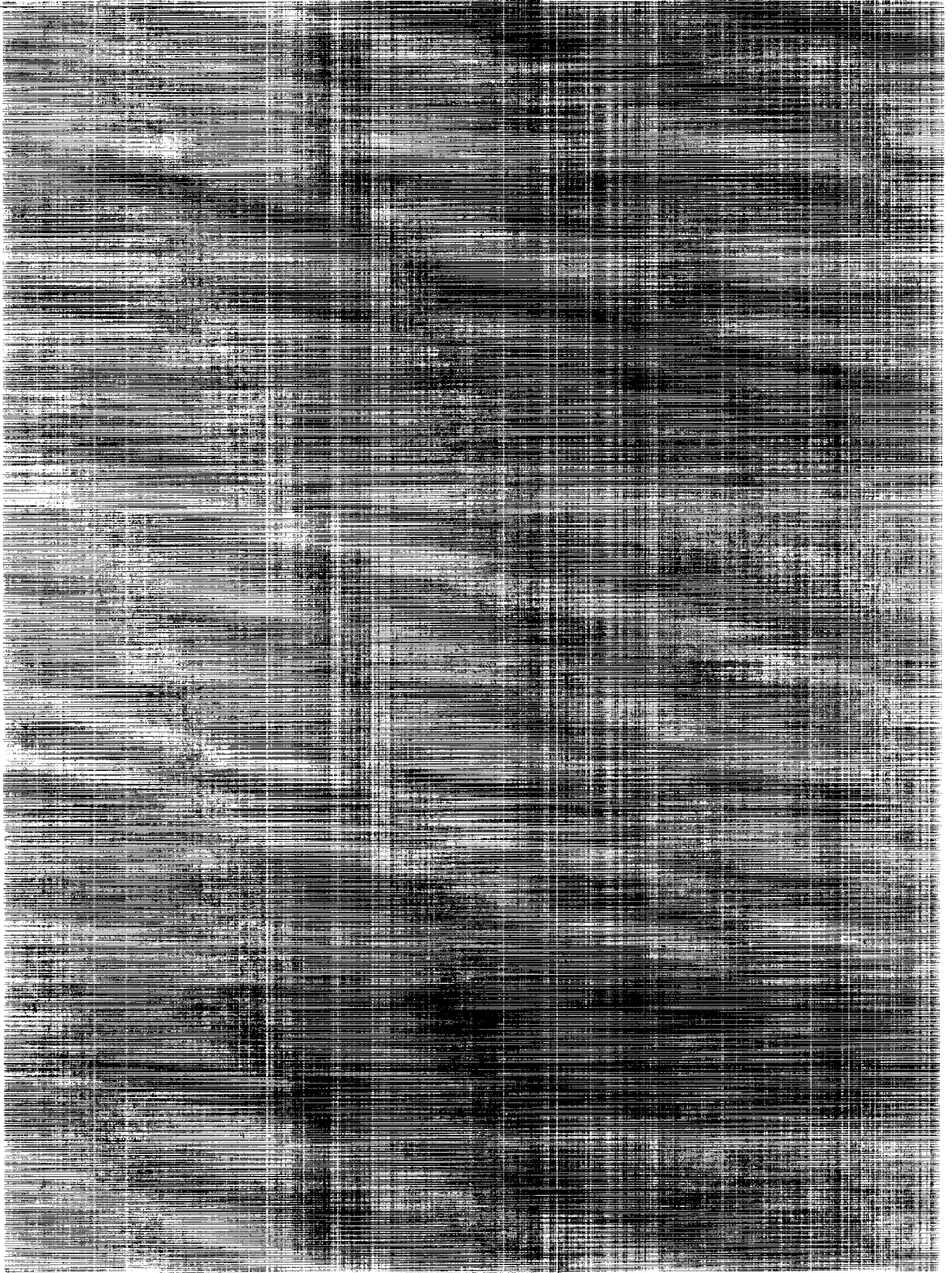
Proceedings of the F-8 Digital Fly-By-Wire and Supercritical Wing First Flight's 20th Anniversary Celebration



National
Aeronautics and
Space
Administration



Proceedings of an
anniversary celebration held at
NASA Dryden Flight Research Center
Edwards, California
May 27, 1992



NASA Conference Publication 3256
Volume I

Proceedings of the F-8 Digital Fly-By-Wire and Supercritical Wing First Flight's 20th Anniversary Celebration

Symposium Chairman
Kenneth E. Hodge
NASA Dryden Flight Research Center
Edwards, California

Proceedings of an
anniversary celebration held at
NASA Dryden Flight Research Center
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May 27, 1992

National Aeronautics and
Space Administration
Office of Management
Scientific and Technical
Information Division
1996



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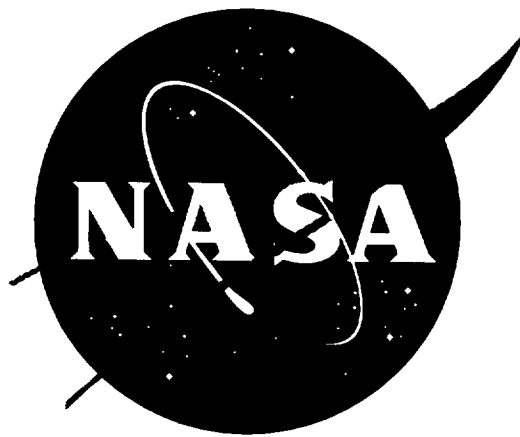
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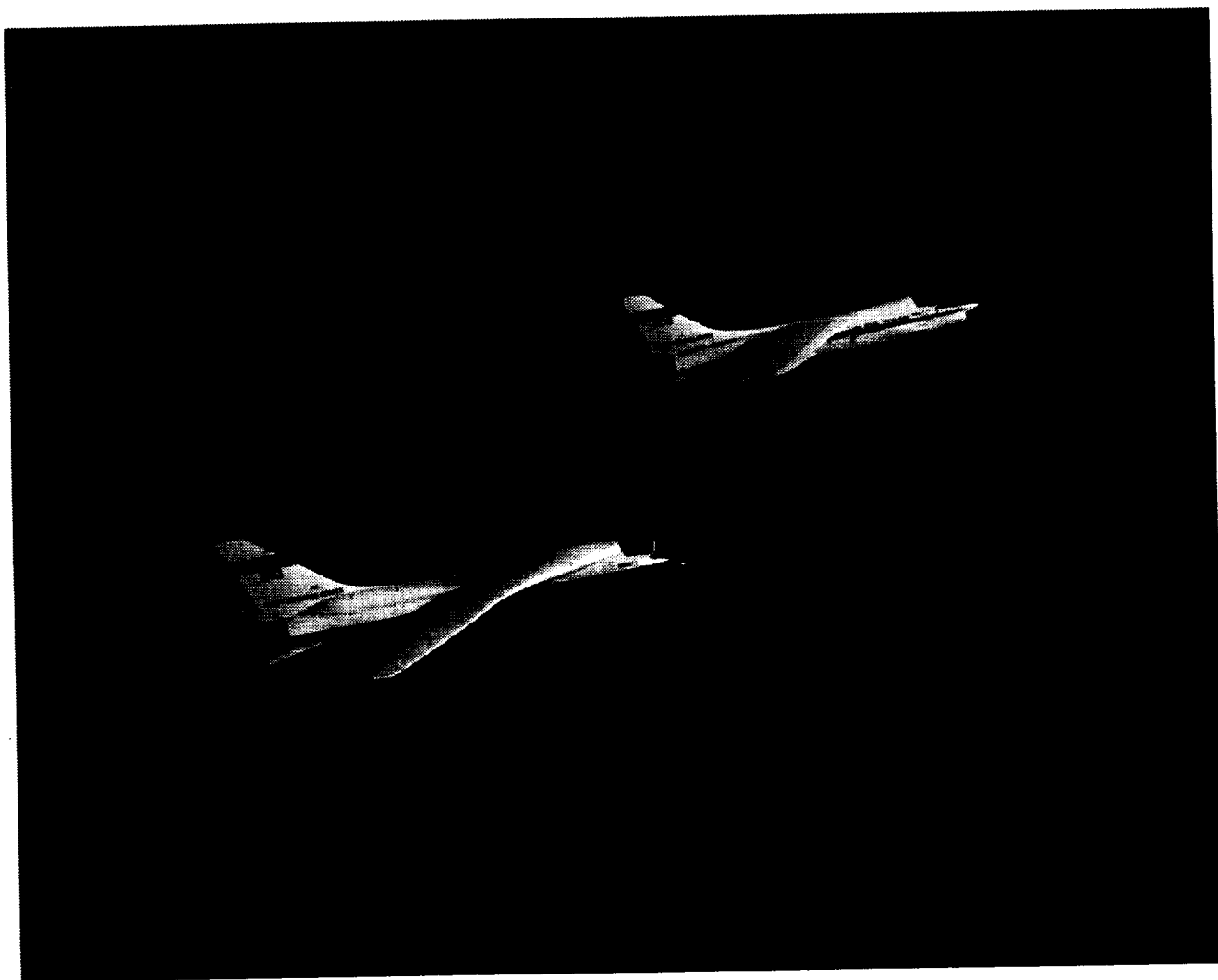
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FRONTISPIECE



PREFACE

Credit for the concept of a celebration and symposium to mark the 20th anniversary of the first flights of the F-8 Digital Fly-By-Wire (DFBW) and Supercritical Wing (SCW) research aircraft belongs to Dryden Flight Research Center (DFRC) Director Kenneth J. Szalai. Under the watchful eye of Chief Engineer Milton O. Thompson, the two aircraft had been brought out of storage by Dryden Public Affairs Officer Nancy D. Lovato and were being refurbished for display as part of the Dryden heritage, joining the presently-displayed X-1E rocket-powered research aircraft and HL-10 lifting body research vehicle. Collaborating with Milt, Nancy had planned a modest F-8 display ceremony for on-site staff once the aircraft were in place on their respective concrete pads.

A ceremony on a much broader scale was requested by Director Szalai in recognition of the 20th anniversaries and the significant role of flight research in adoption of the landmark DFBW and SCW technologies by the aeronautical community. Accordingly, the celebration was expanded to include a technical symposium with a keynote speaker from NASA Headquarters, the display aircraft dedication, a pilots' panel discussion, and a 20th anniversary social event with after-dinner talk by noted aerospace historian Dr. Richard P. Hallion. Participants and invited guests were to include former members of the DFBW and SCW teams, pilots who had flown both aircraft, and the younger members of the Dryden staff.

A small organizing committee was formed and later expanded under Nancy Lovato's leadership to carry out the planning and myriad other tasks necessary to assure an outstanding event. At the risk of oversight, several individuals must be recognized for their service on the organizing committee:

Milt Thompson
DFRC Chief Engineer
Elder Statesman, Advisor

Ed Saltzman
PRC Inc.
SCW Technical Program Chair

Dwain Deets
DFRC Research Engineering Division
DFBW Technical Program Chair

Jim Phelps
DFRC - Flight Operations Division
Dinner Program Chair

Dan Viney
Woodside Summit
Commemorative Medallion Supplier

Stephanie Rudy
DFRC Program Assistant
Luncheon Chair

Joe D'Agostino
DFRC Administration and Technical
Services Division - Facility Support

Don Bacon
DFRC Research Engineering Division
Financial Manager

Louis Steers
DFRC Director's Technical Assistant
Aircraft Displays Chair

Don Nolan
DFRC Public Affairs
Publicity, Invitations, Badges

Marty Curry
DFRC Imaging Technology Branch
Audio/Visual Services Support

Monique Sullivan
DFRC Contracts Management Branch
Procurements

Cal Jarvis
DFRC Aerospace Projects Office
Commemorative Medallion Design Coordination

Cheryl Heathcock
Woodside Summit - Public Affairs
Committee Minutes

Laurel Mann
DFRC Aerospace Projects Office
Registration, Logistics

Karen Richards
PRC Inc.
Historical Exhibits Chair

As an aid to readers, a nomenclature and bibliographies for further reading are provided as appendices.

It has been my pleasure to serve as Program Chair of the Digital Fly-By-Wire and Supercritical Wing 20th Anniversary Celebration and to prepare these proceedings.

Kenneth E. Hodge
Dryden Associate Director

ANNIVERSARY DINNER

May 26, 1992

Rogue Room at the Desert Inn
Lancaster

6:30 p.m. Social Hour

7:30 p.m. Dinner

8:30 p.m. Dr. Richard P. Hallion
"The Gulf Air War: A Survey"

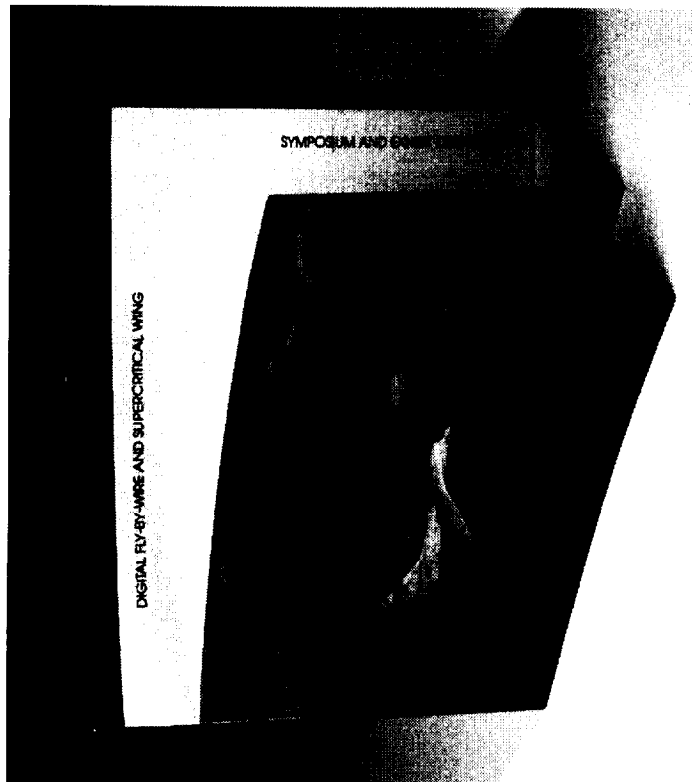
DIGITAL FLY-BY-WIRE AND SUPERCRITICAL WING

AGENDA

May 27, 1992 Symposium

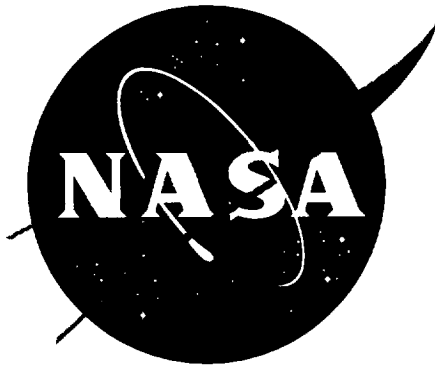
8:00 a.m.	Registration	(ISF)
8:30 a.m.	Welcome	
8:40 a.m.	Keynote Address	
9:35 a.m.	Digital Fly-By-Wire Presentation	(ISF)
11:45 a.m.	Display Dedication	
12:20 p.m.	Lunch & Pilot's Panel	
2:00 p.m.	Supercritical Wing Presentation	(ISF)

Throughout the day - Dryden tours for those interested



Twenty years have elapsed since the first supercritical wing flight and May 25th marks the 20th anniversary of the first digital fly-by-wire flight. In celebration of these two significant events in aviation history, NASA's Dryden Flight Research Facility is proud to sponsor the ...

DIGITAL FLY-BY-WIRE AND SUPERCRITICAL WING SYMPOSIUM AND EXHIBIT DEDICATION



WELCOME AND OPENING REMARKS

Kenneth E. Hodge

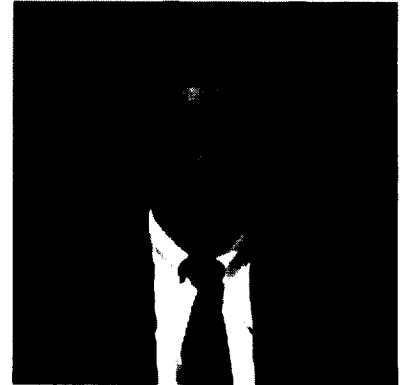
Welcome to the F-8 Conference and Dedication. My name is Ken Hodge; I am the general chairman of this event and my challenge today is to keep us on schedule and be sure everything works smoothly.

According to the agenda, there will be a short break after the third speaker. After the wrap up of the Digital Fly-by-Wire session, we'll proceed to the display area where we will dedicate the two F-8's. Please note that the white chairs are reserved for the original F-8 team members.

Following the dedication we will walk to the Integrated Test Facility which is less than 1/8th of a mile from here for our luncheon and pilots' panel. There are two vans parked in the parking lot behind you for those who might have some difficulty in walking or getting down to the ITF, so please take advantage of that. The vans will also be available to bring you back from the ITF to the afternoon session.

After the luncheon and pilots' panel we will return to this auditorium for the windup of our meeting. Those are the administrative details.

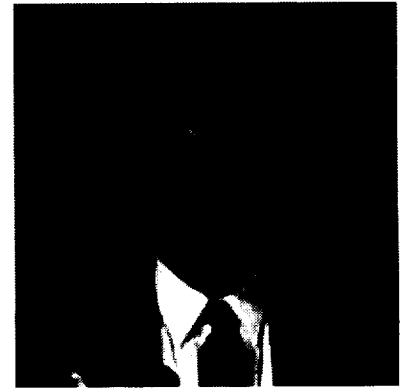
It is now my pleasure to introduce Dr. Dale Compton, Director of the Ames Research Center.



INTRODUCTION OF THE SPECIAL ASSISTANT TO THE ASSOCIATE ADMINISTRATOR FOR THE OFFICE OF AERONAUTICS AND SPACE TECHNOLOGY

Dr. Dale Compton

Thank you very much Ken. It is always a pleasure to be at Dryden and particularly on this occasion. For those of us who started our careers in research, we believed at the time that research was good in its own right, and discovered that we had to justify the research. These two programs we are celebrating today epitomize the justification. I have attended many meetings and advisory groups. Members of advisory groups who are here know what they are all about, and the questions we are always asked are, "Where is the value in this research?" and "How can we show the value?" These two programs show the value in a way that is so evident there can be no question about them.



I don't want to get ahead of the story here. The folks who have been involved understand the technology and applications far better than I, and can tell the story far better than I. I'd like to let them do that. It is my privilege today to introduce the keynote speaker, Richard, better known as "Dick" Kline, who is the Special Assistant to the Associate Administrator for NASA's Office of Aeronautics and Space Technology (OAST) in Washington.

Dick is a newcomer to NASA management, but he'll forgive me for saying so. He's an old timer to aerospace with a 35-year career in the field, most of it with the Grumman Corporation where he served as a senior executive, manager, and technical expert. Immediately prior to coming to NASA he was vice president for their Space Station Program Support Division and before that he was program vice president for Grumman Shuttle Space Systems Technology and Development.

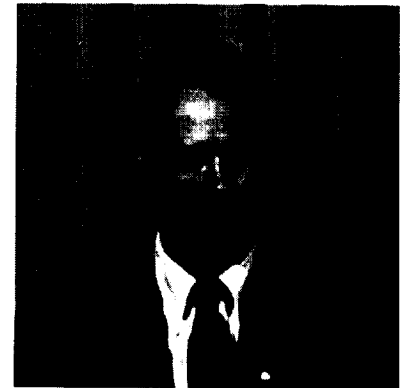
He's a natural for his current position at NASA because of his experience on the aeronautics and the space side of technology development. That is particularly important for the role he is playing in OAST at this time. On the aeronautics side, he was involved in the design of Grumman's A-6 Intruder, F-14 Tomcat, Gulfstream executive jet, and E-2A Hawkeye. On the space side, he was program manager for the Lunar Module Thermal Heat Shield Program for the Apollo era and was technical manager of the Lunar Module Manned Systems Test Program. As you can see, his experience encompasses all aspects of what NASA does.

Dick has served on a number of advisory panels and boards. He has served on the President's Space Commission Utilization Task Force, US Scientific Advisory Board, the Committee on Space Debris, the National Research Council, ASEB Panel on NASA Space Research and Technology Program, and on the NASA Advisory Committee Task Force on the Role of Man in Space. He has been the chairperson of the Aerospace Industries Association (AIA) Space Committee for the past couple of years. Dick has not only played the role of technology manager but also played the role of advisor. Attesting to that are the awards. He's been elected to the International Academy of Astronautics, he's a fellow of the AIAA and several other professional societies, he has authored and coauthored 46 papers of a technical nature and he is a licensed New York State Professional Engineer. It's with great pleasure this morning that I welcome Dick Kline to this podium.

F-8 FLIGHT RESEARCH OF THE PAST - A GUIDE FOR AERONAUTICS OF THE FUTURE

Richard Kline

Thank you Dale. It's a real pleasure to be here at Dryden to join you on this happy occasion of celebrating the 20th Anniversary of the Supercritical Airfoil and Digital Fly-By-Wire Programs. I bring you greetings from Associate Administrator Pete Peterson from the Office of Aeronautics and Space Technology (OAST), who I daresay would much rather be here than wading through the torrents of FY-94 budget plans and the various pressures of red and blue teams. Nevertheless, it is my pleasure to be here in his place. I want to talk to you about three things. First, the environment that we are in from the aviation side; second, some opinions which I have relative to the F-8 programs; and third, what OAST is doing in its strategy for building and strengthening even more of the technology in aeronautics.



Let me turn first to the aeronautics environment. In 1991, just within the United States, the aeronautics business had sales of more than \$90 billion, employing almost a million highly skilled personnel in the process. Of that amount, at least \$28 billion was in exports, and so more than any other industry it helped contribute to a positive balance in payments for our country. The outlook between now and the year 2005 is a doubling in just the air travel side of that business, creating a market for an estimated \$600 billion in new jet transport aircraft. It's exciting and important to us as a country (but many others recognize that same critical importance) and so we see other companies and countries positioning themselves for large participation in that activity. Looking back, American industry sees European and Japanese companies position themselves to do a lot of business, business that we might say is our business. At the same time, we see a decrease in military expenditures which reduces the base from which this activity can go on. Third, we see in the European and Japanese communities increased strengthening of the R & D activity so vital to participation at a later time. It is vital that the United States, both from the private industry and from the government side, do the right things to position ourselves for leadership in the next 13 years.

Within that environment let's look back now at the F-8 programs. We'll hear from many of you who are much more expert than I about those two programs. I want to highlight four things which I think are significant. The first is the selection of the F-8 Crusader Jet from a field of military fighter aircraft, an area where, with stringent requirements, you have a robust airframe with large structural margins with ample propulsive capability to meet those requirements. Then there are the wide flight envelopes. When you couple those flight features with the added benefit of a structural design for the wing which allowed for easy modification, add the fact that the aircraft came at no cost to NASA - the price was right - and even a Grummanite like myself has got to turn back and say that an excellent decision was made for that vehicle.

There are several other important features relative to the program. One is the involvement, right from the very beginning, with the analysts, wind tunnel experimentalists, and then the flight researchers in close communication. Then, the approach of not waiting for the ultimate aircraft (which might never have come; who knows?), but to get on with the job and get early flight research results so that one could build from that for what needed to be done at a later time. Dryden fostered development of dual use technologies, with NASA providing an essential link between military and civil aircraft technology application. Although the

F-8 was a military aircraft, the technologies that were validated—supercritical airfoils and digital flight controls—are broadly applicable to civil aircraft. Finally, there was the feature of getting wide dissemination of the data early. These things coupled together formed the important basis of the philosophy under which this program was directed. The product certainly shows it, because the airfoil activity found its way into commercial vehicles such as the 757, 767 (in which I flew on my way out here), and the MD-11. With the Digital Fly-By-Wire Program, the F-18 quickly picked it up but it will be almost 15 years before it appears in the 777. We've got to accelerate transfer of technology and its incorporation into practice to maintain our competitive edge.

I selected some examples to make a point about the F-8 Program. The F-8 Program was faster, smarter, cheaper while maintaining flight safety throughout the program. This should be very familiar to those of you who have been working with the policies NASA intends to implement agency-wide. I would say that the F-8 Program is one of the harbingers of that kind of activity as we look into it. You have a wonderful heritage here at Dryden in developing and transitioning cutting-edge aeronautical technology.

Where is OAST going? The OAST has drafted a statement of position which I will read to you. Briefly stated, we intend to

“Maintain/achieve world leadership in pioneering high pay-off, critical technologies with the effective transfer of products to industry, DOD, and FAA for application to superior US civil and military aircraft and for the enhanced safety and capacity of our National Aviation System.”

As many of you know from being part of it, we have established a program to bring that into reality. In 1989, NASA's Aeronautics Advisory Committee Task Force on Flight Research recognized the importance of flight research activity and I quote:

“The US aviation community believes that the foreign challenge is, in part, the result of insufficient attention in the US to technology validation - the mid phase of the R & D process between basic research and product application and production. In this regard, flight research has been and will continue to be a major contributor to the successful completion of this critical phase of the R & D chain.”

I say - well said! Now what goes on from here in OAST?

We are now trying to go from that vision to the technical program which is going to attain that result. Even in these austere times, we must craft the best program to bring ourselves forward. To meet our commitment to support the national aeronautics goals, we look first to the highest flight regime, to the trans-atmospheric National AeroSpace Plane activity. Leadership must be provided to a large extent here in the development and in the demonstration of critical technologies. At the same time, we need to turn back and recognize the very high cost that we will face in attempting to do those validation and research activities. That says we must challenge Dryden to come up with creative and innovative ways to keep costs down and to close-couple the technology—as we did with the F-8—back to the NASP program.

The second of the three areas that we are looking at in the OAST Program is high-speed research in the high-speed civil transport regime. Here we focus on two key concerns. First is commercial aircraft community noise; second is atmospheric pollution. Great improvements and progress have been made in these areas, and if we continue in the direction we're going, I think those environmental impediments can be eliminated. We need to focus further on the propulsion and the airframe technology and do those things necessary to give ourselves a better economic advantage in the designs developed in the United States.

The third area is in subsonic aircraft technology. We must recognize that subsonic transports are going to be dominant well into the early 2000's, and we must position ourselves for the proper participation in that activity.

This means going back into flight safety—the ground operations, flight operations activities—and then working in the airframe, propulsion, and flight control areas to provide advanced technology as the basis for design and system enhancements. Our new administrator, Daniel Goldin, has challenged us to become part of a new team, sharing its vision and strategy with all of its stake holders. Its objective is straightforward—find new ways to do things safer, faster, better, cheaper, and make continuous improvement a part of everything we do. All of us need to be part of this team. It's the right objective at this time for NASA within the environment within which we all work—both nationally and internationally. I ask your help.

I also ask your help in seeking and implementing innovative ways to transition our technology to our customers. That is the bottom line, and the ultimate vindication of the work which we do is the extent to which it actually is committed into practice. We must extend our partnership with industry, government, and other parties to be more effective than we have been in the past, although I think we've had extremely good marks so far.

What else can you do? I submit one more piece of advice. Be an active and vocal participant in your program. Talk up the program with your friends and your neighbors. Communicate with your congresspeople, your senators, explaining to them the advantages and value to the American people of having the right aeronautics program for our nation. Don't be afraid to show this off; you're doing something very, very right. You are on the right side of the need. A healthy and competitive U.S. aeronautics industry is vital to our economy.

Programs like the F-8 Supercritical Wing and Digital Fly-By-Wire have shown us the way to bring that technology into practice. We need a strong flight research program to develop the technology base and encourage its transfer into the user community. Let's profit from the outstanding examples shown by these F-8 Programs; use them as models for technology development. Continue the Dryden tradition through sound demonstrations that investment in aeronautics returns real value for our country.

Congratulations to you again, and thank you.

INTRODUCTION OF KEN SZALAI

Ken Hodge

Thank you Dick for that pat on the back and those words of wisdom. I'd like to now introduce Ken Szalai, Director of the Dryden Flight Research Center, who will introduce our next speaker.

INTRODUCTION OF DUANE McRUER

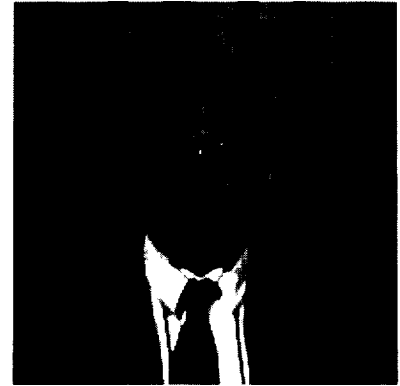
Kenneth J. Szalai

It's a pleasure for me to introduce Duane McRuer, who will focus on flight research, especially its role in discovery. The name McRuer has become synonymous with manual and automatic flight controls, human operator-vehicle systems interactions, flying qualities, and flight dynamics. Some will argue all of these things are really one and the same. I think that more than any other individual, "Mac" has unified flight dynamics, flight controls, and flying qualities.

He is Cal Tech educated, and I guess that I should correct that and say that one of Mac's characteristics is his lifelong education and learning, which is a good lesson for all of us. He was with Northrop between the years of 1948 and 1954 and worked on the Flying Wing during that time. Since 1957 he's been the president and technical director of Systems Technology, Incorporated. He's worked on more than 50 vehicles: spacecraft, bombers, fighters, transports, RPVs, missiles, research aircraft, and ground vehicles. He is the author of more than 100 papers and reports, and 7 books. He's been a major contributor to understanding the design and application of manual and automatic flight control systems.

Perhaps more notable is that he has given a tremendous amount back to the aeronautics and space community. When a program needs a real review, not just somebody just to check a square off, that's when Duane McRuer is called upon by this country, whether it's space shuttles, spacecraft, aircraft, or other complex programs. Mac has been willing to give of himself, sacrifice a great deal, and contribute to this country and these programs. He is on the NASA Advisory Council which reports directly to the NASA Administrator. He was the intellectual force behind really understanding the role of flight research in discovery.

He is a fellow in five professional societies. He was the recipient of the NASA Distinguished Public Service Award and the Mechanics and Control of Flight Award, the prestigious award of the American Institute of Aeronautics and Astronautics (AIAA). He is also a member of the National Academy of Engineering. He's a mountaineer, a student of history, and has mentored many young scientists and engineers, including the one speaking to you now. It's an honor and pleasure to introduce Duane McRuer as a scientist, engineer, mentor, and friend.

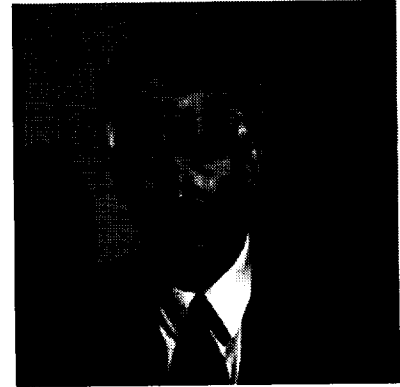


THE CENTRAL ROLE OF FLIGHT RESEARCH IN AERONAUTICS: DISCOVERY AND MATURATION

Duane McRuer

Flight Research as a Central Activity in Aeronautics

A thesis in this paper is that flight research has two quite different facets—discovery and maturation. Technology maturation is the more common function, involving flight validation or flight demonstration. These important aspects of flight research are needed to confirm and fine tune expectations, and to help solve known problems. Such flight programs are undertaken knowing what is sought, at least in principle, and they tend to be terminal phases of an open-loop development process. In the history of aeronautics, by far the most important result of flight research has been discovery—revealing what exists but is not yet perceived (fig. 1). The pioneering flight research programs conducted on the digital fly-by-wire (DFBW) and supercritical wing (SCW) aircraft which we celebrate today have been remarkable examples of technical maturation and discovery categories. Much of this heritage will be recapitulated by other speakers so I am going to focus on flight research in general—but the F-8 DFBW will make a momentary appearance as an exemplary entry.



- **Validation = to confirm expectations**
Know what you're looking for, at least in principle
- **Discovery = to reveal what exists, but is not yet perceived**
Hopes, dreams, and faith—great expectations for novelties

Figure 1. Validation versus discovery.

As shown in figure 2 (adapted from ref. 1), aeronautical research can be depicted as an interconnected aeronautical triad with many feedbacks and crossfeeds among the elements. In combining maturation and discovery roles, flight research becomes a central discipline in aeronautics which is intrinsically interactive and synergistic with the other design disciplines. When the discovery role is involved, the flight research element can become the initial rather than a terminal phase. In either a maturation or discovery role, flight research is indispensable for aeronautical, scientific, and technological advance.

Even a brief consideration of the advantages and limitations of each of the elements in the triad makes clear their complementary, noncompetitive roles in aeronautical developments.

Theory and computation, including numerical simulation, allow the isolated study of known phenomena of interest. Harnessing the power of the computer, many variations can be examined relatively inexpensively by these means. Designs which are optimum in one or more ways can be achieved. Theoretically-based, mathematical representations provide a general framework for understanding, but they are likely to be incomplete in one or more aspects. Thus testing is essential.

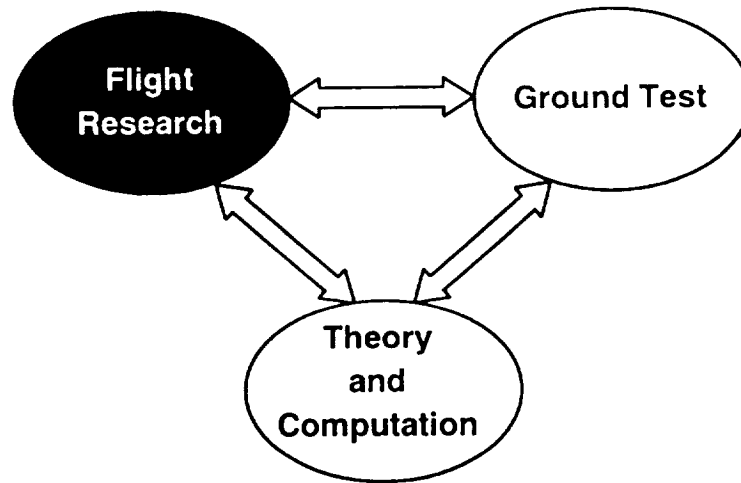


Figure 2. Relationships in aeronautics research.

Ground testing, like mathematical simulations, has the virtue of eliminating some unwanted phenomena from consideration while, it is hoped, adding realism and more complete representations. Frequently, however, some extraneous factors are introduced whose effects are unneeded and, to some degree, uncertain.

Flight research, on the other hand, can provide complete representation and realism, albeit at some sacrifice in the ability to isolate phenomena. Most importantly, it intrinsically includes all the system interactions, foreseen and unforeseen.

Those involved in the design of aircraft always hope that the early flight phases of new aircraft development (which amount to flight research, but is seldom referred to as such) represent only validations, that only fine tuning will be required, and that the designs have sufficient margin and robustness to accommodate all the uncertainties and possibly overlooked phenomena. But, most know that this is not the likely result—something will indeed be discovered in flight as the envelope is expanded. It is hoped that the discovery will be something good, but this is not necessarily the result.

After the inevitable discoveries, theories are revised, foci for future ground tests are changed, etc., as the result of feedback from flight research to the other elements of the aeronautical research triad. Most importantly, the new phenomena discovered become entries in the fundamental database on which aeronautical leadership is based—new insights which offer or can lead to enhanced performance of one sort or another, new problems which must be resolved and accommodated, etc. In short—the bases for understanding and unveiling the future!

Validation versus Discovery

Flight research is a sort of conundrum because its two roles—maturation and discovery—and their motivations, are quite unlike. It is essential to understand and keep the distinctions in perspective (fig. 3).

- **Flight research is incorrectly often equated to:**
 - **Flight validation**
 - **Flight demonstration**
 - **A terminal result of an open-loop development process**
- **Flight research is instead a central discipline which**
 - **Is interactive and synergistic with other design disciplines**
 - **Includes validation, demonstration, and discovery**

Figure 3. Flight research.

Technology maturation via flight validation–demonstration involves tasks which are usually fairly easy to comprehend. By the very definition of validation–demonstration, the tasks are usually the final stage in largely open-loop development processes. And, while some risk is always present when new things are being explored, concrete expectations and estimates are such that outright failure is definitely not expected. Such flight operations can, accordingly, be considered in concrete programmatic and cost terms. Flight is not inexpensive, and this kind of flight research can become very dear indeed. It is therefore inevitable that technological policy makers are tempted to adjust priorities according to financial realities, sometimes to the detriment of the ultimate flight validation–demonstration needed to achieve subsequent commercial viability.

In the evolution of aeronautics, discoveries stemming from flight research activities have been historically dominant (fig. 4). There are good reasons to suggest that this historical trend will continue, even increase. Inherent in discovery is the need to take risks and to accept the fact that there will be failures. Unfortunately, there is no easy way to subject discovery to cost accounting procedures and attitudes. NASA, in its space sciences efforts has shown unprecedented vision and leadership in sowing the seeds for future discoveries in the space arena. Similar vision is needed in aeronautics.

- **In the evolution of aeronautics, flight research for discovery has always been defined by the leading edges of knowledge in the other disciplines**
- **In early aeronautics, flight-based discovery was almost everything**
 - **Hydrodynamic analysis—mainly theory:**
Newton, Bernoulli, D’Alembert, Euler, Navier,
Stokes, Poisson, Helmholtz, Rayleigh, Kirchhoff
- **Experiment—mainly fluid resistance:**
 - **D’Alembert (ship drag); Robins (whirling arm, 1743)**
 - **Reynolds; Philips (wind tunnel, 1885); Lillenthal (whirling arm)**
 - **Langley; Wright brothers (wind tunnel)**
- **Integrated effects:**
 - **Models (Penaud, Cayley)**
 - **Flight (Lillenthal, Wright brothers)**
- **Because integrated effects were everything, theory and basic experiments played only a minor role (except models and wind tunnel)**

Figure 4. Flight research as a discovery process.

Examples of Flight Research Discoveries

Concrete examples of past flight research discoveries include almost all dynamic phenomena of aircraft stability and control (fig. 5). Indeed, weather-cock stability and the longitudinal phugoid are perhaps the only stability and control features which were well-understood theoretically before first flight—and the Wright brothers paid little attention to the first and completely ignored the second! The flight-derived discoveries include pilot–vehicle interactions such as longitudinal and lateral–directional pilot-induced oscillations (PIO), most aircraft-alone modal instabilities such as tuck, directional divergence, nose slice, engine-enhanced phugoid instabilities, inertial coupling, rolling velocity reversals, and a host of other phenomena that have given stability and control aerodynamicists and flight control engineers a steady diet of fascinating occupation and test pilots some interesting moments! The detailed nature of transonic shifts in the center of pressure, shock interactions, buffet, and wing-rock are other examples. Dynamic interactions combining structural, aerodynamic, and control effects, starting with flutter, and propulsion–aerodynamic phenomena can also be cited. Although I have focused here on dynamics, stability, and control because of my background, it is fair to say that in the history of aeronautics, many dynamic phenomena in all the fundamental aeronautical disciplines have been discovered in flight.

These examples suggest that flight testing functions not solely in a validation mode or even in a risk reduction or demonstration mode, but as a means of discovering what is. In this sense, flight research is an indispensable part of the creative process in aeronautics. Modern aircraft are increasingly dependent on the interactions of complex systems to function (ref. 2) and realistic interactions are often revealed only in the flight environment, so flight testing in the discovery mode becomes increasingly important.

- **Vehicle dynamic phenomena**
 - Tuck-under (Mosquito?)
 - PIOs (Wright's, XB-19, F-86, YF-16, YF-22)
 - Deep stall (Curtis XP-55)
 - Lightly-damped quadratic dipoles
- ω_ϕ/ω_d effect
 - rigid/flexible/controls coupling (Snark)
 - Rolling velocity reversals
 - Lateral phugoids (X-13)
 - Inertial coupling
 - Departure
 - Engine-enhanced phugoid instabilities
- **Fundamental engineering problems**
 - Propulsion-induced flow interactions
 - Wing-warp
 - Aeroelastic distortion/trim hinge moments
- **Major ubiquitous integration problems**
 - Pilot-vehicle dynamics/flying qualities
 - Aerodynamics/propulsion/structures

Figure 5. Some typical discoveries in flight research.

A Concrete Example–Pilot-Induced Oscillations

To provide some concrete examples I will present a short series of videos that show so-called pilot-induced oscillations. This topic has been selected for a variety of reasons. First, it is one aspect of flight research which can readily be illustrated to a general audience. Second, although there are outward similarities between the examples, the actual technical details and contributing causes are often quite different. That is, PIOs are, in general, a complex class of diverse phenomena which cannot be simply explained and understood. Third, as the examples chosen will attest, such phenomena permeate aviation's history, and are with us today. Indeed, a comprehensive understanding of PIOs remains a major problem in flying qualities research. While much is known and understood for specific examples (see e.g., refs. 3-6), further understanding is needed if PIOs are to reliably be estimated and alleviated.

As noted in figure 5, pilot involvement in oscillatory behavior was first demonstrated by the Wright brothers. There is a famous on-board movie sequence from a 1908 flight of the Wright Model A of a steady-state pitching oscillation. Because the airplane was longitudinally unstable, the pilot had to exert a stabilizing influence, and the resulting oscillation was normal and routine rather than a big problem.

Skipping a few decades to the immediate pre-World War 2 era, we have the XB-19, a giant experimental bomber. This is shown in the first video sequence, but this time the operation was distinctly abnormal.

The next example is much more dramatic and deadly. These remarkable movies show the second pass of an attempted low-altitude 3-kilometer record run by an F-4 conducted at White Sands on May 18, 1961. The airplane's envelope had not been pushed to the dynamic pressures involved in this very low altitude pass, and the pilot was understandably apprehensive. The night before the record try he indicated that he would trim the airplane nose up, so that if anything happened he could just let go, but he didn't!

The next sequence shows a somewhat premature first flight of the first operational fly-by-wire fighter, the F-16. The operations of this pilot-aircraft system seemed quite ambivalent—was this to be a taxi test or what? Remarkably, the great skill of the pilot (Phil Oestricher) saved the day, but just barely!

On October 26, 1977, another fly-by-wire craft, this time of the digital variety, had its day on the news hour. The approach and landing tests using the shuttle Enterprise culminated in this famous sequence which, in detail, exhibited several PIO modes.^{3,4}

These dramatic events, and other less-well photographed PIOs, have received a great deal of attention from the community comprising test pilots and flying qualities, stability and control, and flight control engineers. As it turns out, while the general nature of the aircraft's oscillatory behavior can be readily appreciated from the visual evidence, sometimes supplemented by detailed quantitative data, the underlying pilot and aircraft behaviors which can combine to create such devastating results are remarkably diverse and difficult to understand.

Figure 6 gives a breakdown of some of the known major factors associated with PIOs. Some of these are complicated or even arcane in themselves, and still more complex in their interactions. One of the simpler causes among the major airplane factors is the net high-frequency lag of the effective aircraft-stability-and-control augmentation system (SCAS). Excessive values can guarantee that a PIO will occur sometime, somewhere. One of the flight research discoveries that can be attributed to the Digital Fly-by-Wire F-8 is the definitive data point in this regard. The actual flight sequence is shown in the next video.

- **Aircraft dynamic characteristics**
 - **Undesirable effective vehicle dynamics**
 - **Controller rate and position limits**
 - “PIO syndrome”
 - Unfavorable quadratic dipoles
 - **Manipulator force and displacement characteristics**
 - **Vehicle dynamics transitions**
 - Stick-fixed/stick-free
 - Vehicle dynamics form changes
 - Moding transients
 - Triggering disturbances
- **Pilot behavioral characteristics**
 - **Excessive pilot gain**
 - **Inappropriate pilot adaptation**
 - **Improper pilot behavioral organization**
 - **Transitions in pilot behavioral organization**
 - Pursuit to compensatory
 - Precognitive to compensatory
 - **Locked-in resonance/precognitive lock-in**

Figure 6. Pilot-induced oscillation fundamental factors.

In sporadic experimental work attempting to elicit quantitative understanding of those PIO phenomena associated with time delay, a fairly large database has been gathered using simulators of all sorts, fixed and moving ground-based, and airborne using variable stability aircraft. Ground-based simulators have usually been poor quantitative predictors of PIO tendencies. As shown in figure 7, the pilot ratings for simulators

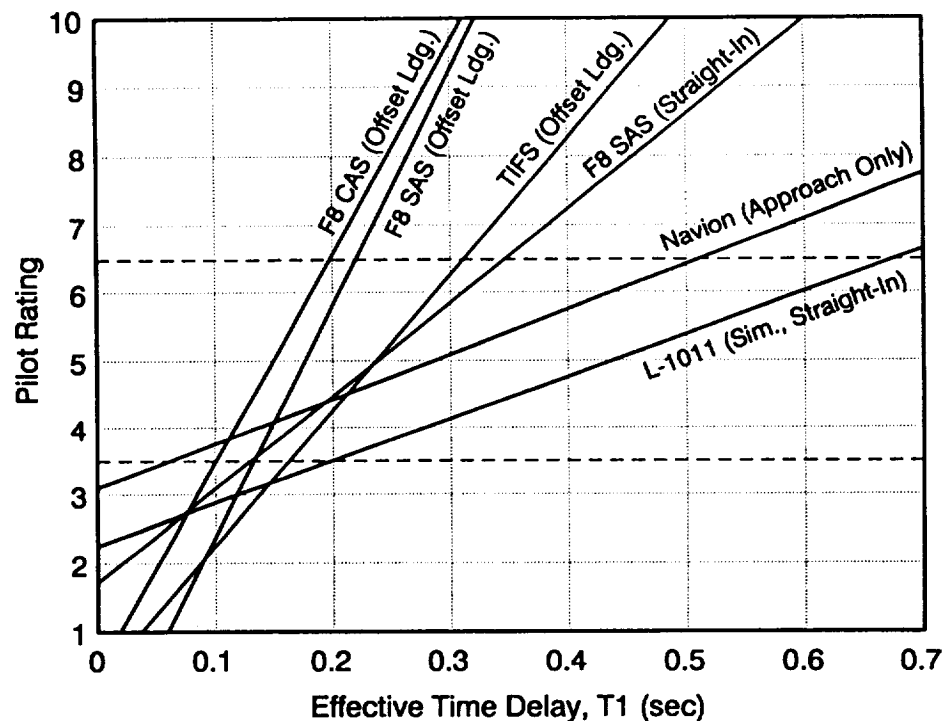


Figure 7. Allowable effective time delay.

and even for relatively benign airborne tasks are only moderately sensitive to effective time delay. But, for crux moves with high attentional demands and focused purpose, the time delay can be of paramount importance. As previously noted, the DFBW F-8 results are definitive here. Indeed, the allowable effective time delay (not to exceed 0.10 sec for Level 1 flying qualities) in military specifications reflects these data.

Many of the entries in figure 6 are still highly qualitative and obscure, so complete understanding still eludes us and these interactions are still important issues yearning for flight research discoveries! That our advanced appreciation is still insufficient is probably best illustrated by the last video sequence, showing the recent unscheduled YF-22 landing which is current indeed (April 25, 1992).

Has the Age of Discovery in Aeronautics Passed?

At the outset the answer to this rhetorical question is a resounding “NO!” Some of the reasons are listed in figures 8 and 9. Discovery possibilities are always present when understanding is inadequate and when flight regimes are extended. The probability of discovery is also very high at performance margins—boundaries and when underappreciated interactions are present. Discovery in flight research is most commonly associated with integrated and overall systems effects. Although models, computation, and theories are all enormously advanced, the leading edge for the ultimate integration which occurs only in flight is correspondingly extended. The interactions between technical disciplines are much closer, the frequency ranges of interacting phenomena are enormously extended, scalings for model experiments cannot duplicate flight, etc. The effective vehicle is no longer an airframe fitted with an engine, but is an integrated aero/structural/propulsion/control system, with each of the disciplines introducing their own dynamic effects and coupling with one another. Further, for manned aircraft, the interactions with the pilot within the system not only remain with us but are augmented by new considerations. Flying qualities continue as a predominant theme, extended and complicated with issues involving living with automation, flight management, and divided attention workloads, all providing new interactive phenomena.

One of the most notable conclusions of reference 2 is the ubiquitous presence of interactive disciplines cooperating dynamically to create aircraft of the future. The physical manifestations of these dynamic interactions are efficient and highly advanced designs—and, implicitly, many new discoveries. Discoveries found in the course of flight research will, in many cases, have to lead the way to these new horizons.

- **Flight discovery today is still heavily associated with integrated effects but at a much higher level. Models, computation, theory all enormously advanced but**
 - **Frequency ranges of phenomena enormously extended**
 - **Interactions between technical disciplines closer**
 - **Incompatible scalings for model experiments**
 - **Interference effects in experiments**
 - **Theory often ahead of experiment**
 - **Flight environment extended**

Figure 8. Reasons why the age of discovery in aeronautics has not passed.

- **Most important involve closed-loop system phenomena introduced by the Wrights, with their appreciation of pilot-vehicle closed-loop operations**
 - **Continue to this day in the guise of “flying qualities” as a major purpose for flight research**
 - **Generalized now to include automatic systems, broader frequency ranges, involvement with more systems, etc.**
 - **Notable on VTOL, rotorcraft, and propelled hypersonic craft**
- **Vehicle-alone dynamic interactions**
 - **Edge of envelope**
 - **Flow-field interactions**
 - **Transition**

Figure 9. Dynamic interactions, a hot bed for discovery.

Planning for Discovery and Future Advances

Full-scale aircraft and special models are the bases for empirical discoveries and developments in aeronautics. As previously described, full-scale flight research activities are essential for leading-edge and highly integrated effective vehicles. In the past, research aircraft have played prominent roles, and to some extent they will continue to do so. But for reasons of cost we have to take advantage of other, already existing aircraft modified for experimental purposes.

In its flight research study,⁷ the National Research Council's Aeronautics and Space Engineering Board (ASEB) concluded that a national focus on flight research is needed. The ASEB recommended that a National Research Aircraft Enterprise be set up to assess requirements for flight research for validation and discovery and to promote and advocate experimental and proof-of-concept aircraft. This enterprise should be national in scope, with DoD and NASA as governmental partners appropriately assisted and advised by industry and academe.

In conclusion, I've emphasized discovery as a major theme in this talk. An obvious question is, “How does one configure a flight research program to guarantee discoveries?” This impossibly simplistic question has no simple answers. But we can search technological history for insights and parallels. James Burke's “Connections,” as shown on public television a few years ago, showed again and again how apparently unconnected devices, ideas, and concepts can often interact, via the medium of a prepared mind, to create new visions and understanding. Daniel Boorstin's “The Discoverers”⁸ is also full of inspirational analogies. Some of the more obvious generalities gleaned from experience are summarized in figure 10.

- **Discovery is most likely to occur to the curious and prepared mind, searching for understanding**
- **Discovery possibilities are almost always present**
 - **At the margins/frontiers**
 - **When understanding is inadequate**
 - **When flight regimes are extended**
 - **With underappreciated interactions**

Figure 10. Prescription for discovery.

Aeronautical history makes clear that where advanced flight research is involved, the unexpected is just around the corner and we must be prepared to make the most of it. After all,

“There is a tide in the affairs of men,
Which, taken at the flood, leads on to fortune;”

And, if we’re not prepared, Shakespeare finishes with,

“Omitted, all the voyage of their life
Is bound in shallows and in miseries.”

ACKNOWLEDGMENT

Some of the material contained herein initially appeared in the ASEB White Paper on flight research, reference 7.

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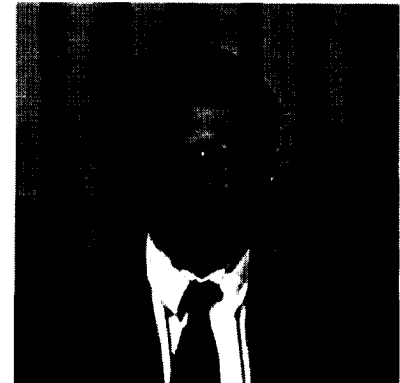
Ken Hodge

At this point, Ken Szalai will take the podium again to make retrospective remarks about the F-8 Digital Fly-By-Wire Program, the harbinger of today's systems-dominated airplanes, and he will also introduce our third speaker.

THE F-8 DIGITAL FLY-BY-WIRE AIRCRAFT; HARBINGER OF TODAY'S SYSTEMS-DOMINATED AIRPLANES

Kenneth J. Szalai

We are focusing on the original F-8 Digital Fly-By-Wire (DFBW) aircraft, and as I looked at it in the last few days, this program and aircraft served in the following ways. First, it was not a one-shot demonstration or validation. The F-8 DFBW program was a link between the Space Program of the 1960's and the Aeronautics Program of the 1970's. Digital computers were very rare in airplanes before 1970; in fact, at Dryden we only had a digital computer in one airplane (a Honeywell Alert computer installed in an F-104 for a guidance experiment). In the Apollo Program, however, the Lunar Module and the Command and Service Module had full-authority, digital fly-by-wire control for the lunar landing and entry.



There were many things transferred from the Apollo Program to the F-8 Program. The guidance, navigation, and control system from the Lunar Module was used as the core hardware system in the F-8. This reduced the cost and schedule significantly. It also ensured a high level of safety because of the integrity of the hardware. We also used much Apollo software, which included the operating system and a large amount of utility software. This also contributed to reducing the cost and schedule of the F-8 Program.

In addition, there was the transfer of expertise and experience. I think of two organizations specifically—the Draper Lab, and AC Spark Plug, now Delco Electronics. I remember the Phase I Program people—Al Engle and Bob Bairnsfather. We also have in the audience today Phil Felleman, Vince Megna, Bob O'Donnell, and George Silver. Their expertise is an enormous national asset. The Draper Lab is one of the success stories of this country's advanced technology work. On the AC Spark Plug side, I remember Ken Adamek and Ben Beh. Ken is here today. I remember when the AC Spark Plug people came in and refused to open their boxes of hardware because the area was too dirty. They insisted on vacuuming all the sand before opening the boxes and powering up the precious Apollo hardware. The sand blew in again after they left, of course, but it never affected the operation.

The Draper Lab and AC Spark Plug experience transferred from the space program to aeronautics was significant. The enormous infrastructure of these two organizations also transferred, which included systems and software design processes, software management, configuration control, and verification and validation processes. This was a major reason for the quick advance we made in this technology.

The second contribution of the F-8 DFBW aircraft flight program was that it was certainly a milestone in flight. It was the first true fly-by-wire and the first true digital fly-by-wire aircraft without any mechanical back up. It unshackled designers and allowed them to select configurations and stability levels that were previously forbidden. It was a significant force in changing the course of aircraft design. At this point I would like to note the pioneering work done by the US Air Force on the F-4 Survivable Flight Control System and later on the Advanced Fighter Technology Integration (AFTI)/F-16 DFBW flight control system. These advances enabled the transition of digital fly-by-wire technology into military aircraft.

The third role of the F-8 DFBW program was as a prolific and productive flight research facility. After the first flight of the F-8 on May 25, 1972, the program engineers developed a Fault-Tolerant Triplex DFBW System in 1976, which pioneered techniques in sensor, computer, and actuator redundancy management. Research was done in analytic redundancy management with Langley, the Draper Lab, and with

MIT. We also conducted experiments using real-time parameter identification. This involved an adaptive control experiment done with Langley and Honeywell. Gary Hartmann, who is here today, designed the advanced control laws for the F-8 and also developed the adaptive control system. We did work on side stick force control and a resident back-up software system. This was a back-up software system approach which has found its way into use in several aircraft. We also did a great deal of work in channel synchronization. I estimated that there were about a quarter of a billion sync cycles on flight software without the single loss of sync. We explored very low sample rates in an experiment run by Dick Larson. Kevin Petersen developed the F-8 remotely augmented vehicle approach which closed the aircraft control loop with a control law computer on the ground. This led to the new uplink control and display techniques we use on most airplanes at Dryden. Different design philosophies were used and all have been made to work, including synchronous and asynchronous systems. I mention at this point the pioneering advanced asynchronous systems work done on the AFTI/F-16. Colonel Harry Heimple is in the audience; he ran the AFTI/F-16 CTF here. It was a very successful program, and evolved into a very productive and important research and development facility.

The fourth contribution was the training of many people. Cal Jarvis is not here today; he's working an important NASA activity. He is an outstanding project manager who made this program succeed. The F-8 Program also trained our operations engineers like Jim Phelps. He had the responsibility of finally qualifying and certifying the aircraft for first flight. In addition, the program provided training for simulation engineers, flight control engineers, software managers, PI's, safety personnel, operations engineers, pilots, ground crews, instrumentation crews, procurement staff, ground testers, contractors, and our own management. Spouses learned that getting a software program to run right meant long hours at work.

I would also like to call attention to our aircraft crews. They have the ability to deal with airplanes that have new wings installed in place of the ones that were removed, and new electronic flight controls replacing mechanical systems which were torn out. This causes havoc with the TO manuals, processes, and procedures, when one starts yanking out the mechanical controls and pulleys and things that you've greased and loved all those years. Jim Hankins, who has since passed away, was the crew chief on the F-8 DFBW and he asked the question that is still the principal question in digital flight controls today. At first, when everything was working fine, there were no questions. We all marvelled at the new technology. But then we had our first anomaly, the very first anomaly, and all of a sudden Jim Hankins got very, very suspicious. He looked at the computer and he came over to me and said, "How do I know what's in that box? ..." and I guess that's still the unanswered question. People have made careers and billions of dollars trying to answer that question.

Finally, the F-8 was a link back to the Space Program. It was really a pathfinder for the AP-101 flight computer. We found some problems with the computer, but it led to a better computer that ultimately went into the Space Shuttle. The F-8 also tested shuttle software modules and control time delay effects, as Mr. McRuer mentioned. The F-8 went on to support the development of the pilot-induced oscillation suppression filter.

These activities were part of the discovery process and were much more than mere "validation" activities.

One thing this program made clear was that we had to let people do their jobs. It's a popular thing now to use the word "empowerment," but that's been the byword here for many years. The line supervisor during these years, and the first PI on the program, was Dwain Deets. As a line supervisor during this time, he advised and empowered people to do their jobs. I'd like to introduce the line supervisor that guided me and others through these years. Dwain Deets is acting chief of the Research Engineering Division.

THE STATE OF TECHNOLOGY BEFORE DIGITAL FLY-BY-WIRE

Dwain Deets

Thank you Ken, I'm not sure there's anything more to be said about the program after that, but I'll see what I can do. I'm going to start by taking a look at the state of the technology going into the program; the things we thought were the important things that the program would contribute to. The first slide (fig. 1) is my outline.



- **The promises**
- **The technical issues**
- **The arguments for flight**
- **Changes in thinking**

Figure 1. The state of technology before F-8 Digital Fly-By-Wire.

First of all, we thought—and the advocates pushed as the promises that the program offered—how could it affect airplane design and the payoff, and then we'll go through the various technical issues as we understood them. A little about why we need to do this in flight to actually make sure that you understood the answers and that you had the credibility with these people. How this affected the change in thinking of people, the culture that was here and used to the ways of doing it in the past.

Starting with figure 2, the easiest thing to explain was that you can save airplane weight if you can rely on digital fly-by-wire. "Control configured vehicle" was the term that we used; it featured a smaller tail and various other things. That really needed to be the argument because it resulted in the largest improvement in performance and weight savings so people could understand. A lot of what we had to do in saying "Why do this?" was to show this could actually change the configuration later on. We did studies showing how you might put a canard on the plane; we weren't so sure that anyone would have to believe that you might do that, but we did it anyway.

- **Weight savings (control configured vehicles)**
- **Improved reliability and maintenance**
- **Greater adaptability**

Figure 2. The promises.

Then, the idea of improving reliability and maintainability by having a lot of soft checking that goes on once you got the digital computer there. It not only does the control laws but it does a lot of the other things to monitor the health of the airplane and the health of the systems. This is something that was happening in the space world and their applications; so we said, if it works there we certainly can apply that to aeronautics and get those kind of benefits as well.

The third thing is that the software part has greater adaptability to make changes and the gee-whiz kind of thinking is “Well, you can have whatever hardware you have and if you have any problem right at the end, before you need to fly, then you just change the software.” Zap it in there and you’ve corrected your problem! That was the promise—but we found it’s really not that easy—it took a lot of effort to correct.

Going through the technical issues (fig. 3), digital fly-by-wire has several aspects. One was that it was a digital flight control system, whether it was a fly-by-wire system or not, the part that says how a digital computer affects your ability to design a good flight control system, or how might it interfere with stability and pilot-airplane interfaces. That was a whole area of technology that opened up its own possibilities for research.

Digital

Single-channel Issues

Sample-Rate Effects

Computational Delay

Failure Mechanisms

Redundant-channel Issues

Interchannel Communication

Synchronization

Generic Software Errors

Fly-By-Wire

Authority Level

Power Systems Redundancy

Single-point Failure

Independent Backup

Verification & Validation

Figure 3. The technical issues.

Given that it was a digital system, it could either be a single-string system, or single-channel single computer, and have those kinds of problems. If it were a multi-channel system, a redundant cross channel comparison, then there was a lot of communication that had to go on between the different channels, and how you synchronized the channels. That was a whole different set of technical issues that needed to be addressed.

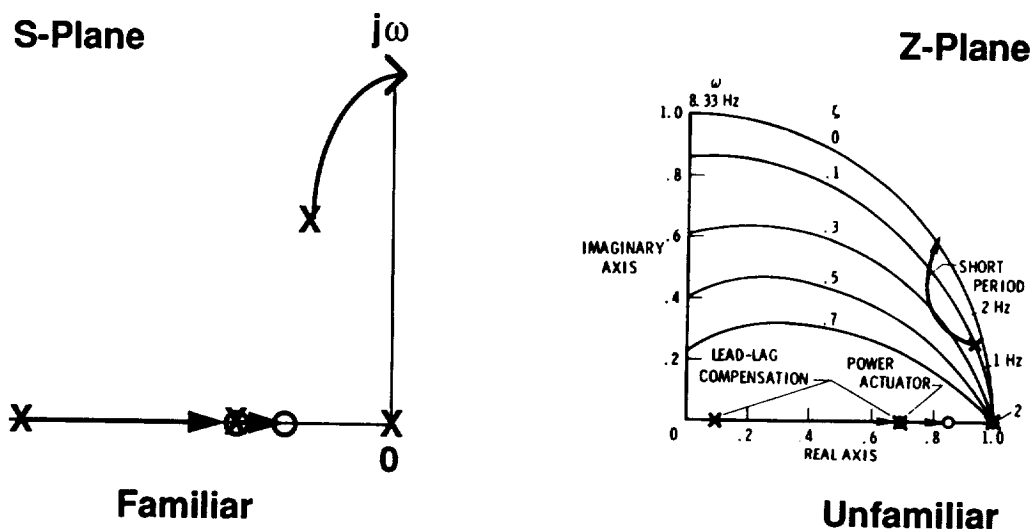
Under the term “redundant-channel issues” I also had a generic software issue. You could have all the same software running in each of the computers, then it would really be a single-string failure even though you had a redundant set of channels.

On the other side is digital-fly-by-wire where you have removed all the digital back-ups and all the mechanical back-up systems. That was a whole different set of challenges and technical issues that needed to be addressed. By coupling these two in one program, a lot has been addressed across the board.

Last is the whole subject of how do you verify and validate this total system to convince yourself it's all working right. That ends up in being a technology in itself. Kind of a technology in the processes that you use that end up being convincing to yourselves and to others that you have done your job right.

Back with the pure digital flight control single-string kind of issues, sample rate (fig. 4) was one that an awful lot of time was spent discussing "What sample rate did you have to have?" When we began this program, computers were not fast like they are now; they sort of plugged along. You imagine that you're always going to be faced with sampling slowly relative to what you're trying to control, the modes that you interact with. The question is, "What analysis tools do you have to use?" I'm showing two different analysis tools that are typically used. There's a whole set; S-plane analysis is an example of a continuous system, an analog system analysis technique. This is what all of the control law designers that you had faith in use because they've seen the kind of problems you get into; you ask them which one you need to use and they would also say, "Well the kind I've always had, the continuous system." This is an example where you got roots and poles to indicate dynamic characteristics of the airplane on the S plane; where the arrow goes across the vertical axis to the right, you go unstable.

- **Are unfamiliar design/analysis approaches necessary?**



- **How high a sample rate is necessary?**

Figure 4. Sample-rate issues.

The Z plane is what was used for digital systems, sampled data systems, and that was a common analysis technique for people that were number one in universities, who had done a lot of paper studies, but hadn't reached the point where it actually was applied to real airplanes that had to fly. So you have the group of people that feel very comfortable with Z-plane analysis that included the sample rate effects, but they weren't the people that had been through programs. So part of the problem is: do you really have to go to this Z-plane analysis or is there a way of approximating the effect of the sample rate and still be able to use the tools that you're used to? There are other things such as Bode plots—a whole cadre of tools that help you to better understand the system.

The bottom bullet here: how high a sample rate is necessary? We ended up looking at a lot of different sample rates. We had to freeze a design on a particular sample rate once the schedule said you had to freeze a design in order to be able to fly when we said we would. We did a lot of studies that said, “Do I need to sample twice that fast?” and simplify the design so the computer could do it? We had this uneasy feeling that maybe we hadn’t selected a high enough sample rate and we’d have problems later on.

Figure 5 addresses the question of computational delay. The horizontal bar here is a time slice, a compute frame where at the left-hand side is the start of the compute cycle and the right side is the end of that compute cycle or the beginning of the next compute cycle. You need to do all of your sequential computations before you get to the far right side. You want to get your answer out—which is control surface command—as quickly as possible.

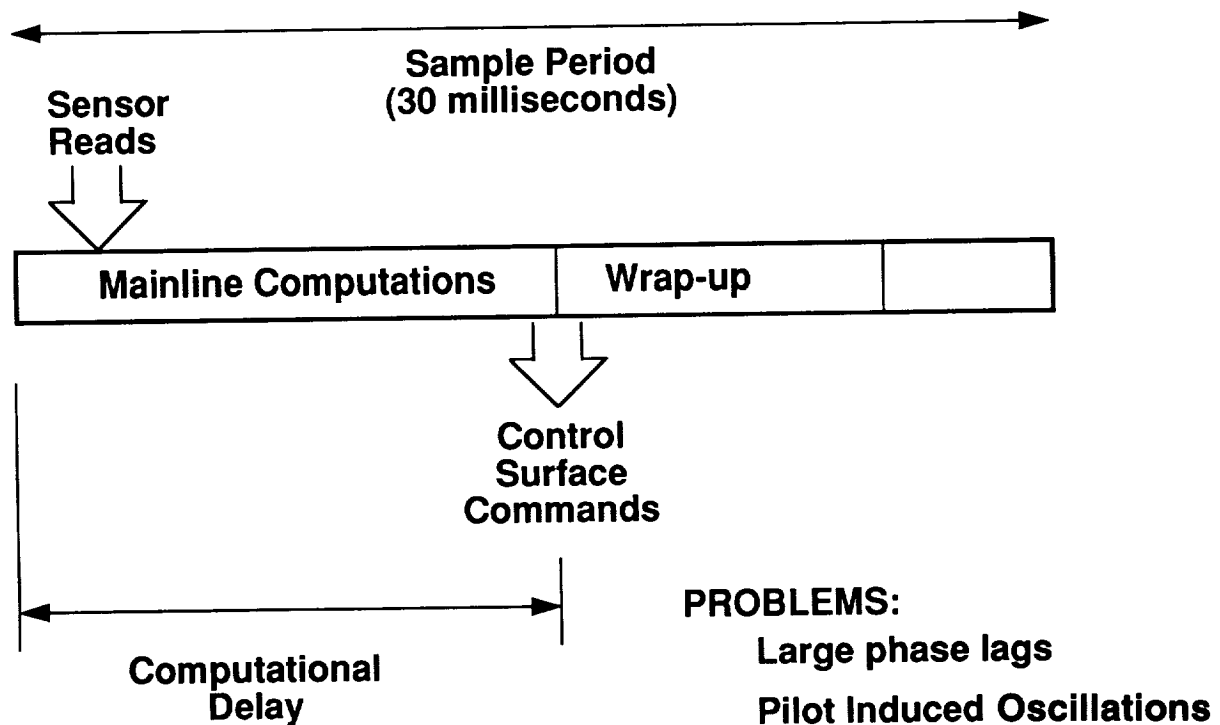


Figure 5. Computational delay issues.

By breaking up the software into a set we’ll call mainline computations, only those things you need to do to get to the next command, you then save the things you have to do later for the wrap-up. It’s a way of minimizing the length of time from this computational delay that’s within the digital computer. There’s concern as how much delay can you stand and not cause a phase lag that would cause a pilot-induced oscillation or stability problem just in the closed loop around the airplane.

This figure shows an ideal computational delay. It assumes that when you sampled there at the sensor read point (the information that pertains to the sensor), it was probably sensed somewhere in the earlier frame, so there was a lot of average delay before you even got to that point. At the control surface command, when it goes out it may go to a buffer that holds that information until another sample comes along and sends it on to the control surface. So, there were a number of different sources of delay; this is just the one that we tend to focus on to show the difference between a digital system, fundamentally, and an analog system. You really have this delay; on an analog system you don’t have it. So, how are we going to be impacted by these additional delays?

Here are the problems that we worried about: the phase lags, whether or not we had pilot-induced oscillations, the way of breaking up the software into packages of the mainline computations, and the wrap-up. That was something that was being done in the Apollo Program so we inherited that approach. It looked like a sensible way of doing it so we passed it on to others as we gained experience.

The whole question of handling failures (fig. 6) - the failure mechanisms (how do you detect them, what do you do about them) is another subject. First, the unfamiliar failure points; unfamiliar to people who deal with, for example, black boxes. Ken mentioned the question, "What is it doing?" that shows there's a real fear here that since you have a digital computer where if one bit changes, you could have a dramatic change in the level of command at the surface. You never know when that is going to occur on the output—on an unexplored path in the logic ... a whole set of mysterious new failures.

How do you detect these kinds of failures which are application independent? We inherited the software and the hardware from the Apollo Program and we used a lot of the detection equipment, built-in tests and things that were valid no matter what you had. The fact that we were applying it to an airplane with flight control laws, that would be the application and it was independent of these other kinds of tests. There would be systems software checks to make sure the operating system was doing what it was supposed to do. So a lot of self-checking was inherited with the system. For our application we added another set of checks to our flight control laws; checks to make sure that a control surface command didn't seem unreasonable between one compute cycle and another.

Unfamiliar failure forms

Bit failure could have dramatic repercussions

Failure detection

Application independent

- **Hardware self-check**
- **System software self-check**

Application dependent

- **Reasonability checks**

Failure accommodation

- **Restart**
- **Restructure (downmode)**

Figure 6. Failure mechanisms.

Once you detected a failure, the next question was, "Well, what do you do about it?" The Apollo Guidance Computer had a restart capability which allowed the program to start over with a known set of information at any point. Then the question was, "What information should you save so that if you ever have to start over within a compute cycle, you have a safe situation and can press ahead." A lot of thought was given to this question. It was well understood on the space side, but for us in aeronautics without a lot of experience, it was quite a learning process for us to figure out the sensible thing to do.

These are the issues and questions that we had to think through and make sure we understood well so we could explain them to other people who were not familiar with it.

And if you don't want to just restart and continue in the primary mode, then you would go to some downgraded mode that might be a different mode within the digital system, or you don't have one of the primary sensors, or you go to a back-up system avoiding use of the digital system altogether.

With the redundant channel issues (fig. 7) there was a different set of problems. How much information needs to be communicated between the different redundant channels? That was a big question then, because the more information you transferred back and forth to convince yourself that all channels were working correctly, the more time it took to do that and the more processing time to figure out whether the information was what you expected it to be before you could proceed. The opposite approach was to have an absolute minimum of information transferred between channels, and if that minimum information isn't right then we shut the channel down and not take as much time. So we did trade studies to see what was right.

- **Interchannel communication**
- **Synchronization**
- **Generic software errors**

Figure 7. Redundant-channel issues.

The synchronization question continues today even after the F-8 Program—there are still differing views on what is the way to synchronize between redundant channels. The tightest connection would be a bit-for-bit synchronization. Every bit of information that went into one channel you assure yourself it went into the other channels exactly the same way. Also, the computations started exactly the same so there would always be a one-for-one comparison. We chose a looser form of synchronization, a frame synchronization, where the computer was started on a computational cycle. Each channel was slightly different, but if they were a little bit off we would make them closer as time went on. It gave you some flexibility but was still a good solid system.

The other extreme is asynchronous, where there is no attempt to match the computer cycles. In fact, you would not want the channels lined up with one another; they would run independently and then you would sort out the information as you transfer back and forth. There was a tremendous amount of time spent on this question.

The generic software error is really the question “What happens if something you haven't thought of is programmed wrong in the software and it's in all of the computers and it just wipes you out and shuts all channels down?” A tremendous amount of time has been spent trying to figure out how to be systematic in approaching this question, but there's never a final answer because there's always one more problem that you hadn't thought about.

Moving to the fly-by-wire issues that are not dependent on whether you have a digital system or an analog system (fig. 8) - the first one is that it's full authority by definition if you have no mechanical back-up so that a failure can overstress the airplane, so that becomes a question of how much, what do you have to do if it's full authority and the airplane integrity is at stake versus the experience that was then available from past systems with limited authority, where a problem wouldn't endanger the airplane.

- **Authority level**
- **Power-system redundancy**
- **Single-point failure**
- **Independent backup**

Figure 8. Fly-by-wire issues.

The power system redundancy relates to the electrical power and hydraulic power. How do you make sure that those have the same level of reliability that your digital system has in doing its electronic comparisons - so that had to be thought through very carefully.

The single-point failure, other than a software failure, we worried about. If you have a single-point failure that can cause one of your control surfaces to go hard over, how do you protect yourself and convince people you've found all the possibilities? We believed an independent back up was needed, and therefore we had an analog back-up system that was FBW and was independent from the hardware channels.

Verification and validation (fig. 9). How do you qualify (man-rate) the software when a life is at stake? Putting this process together and bringing it to an aeronautical application was as much a part of the experiment as the hardware and software. How we did it, what processes we followed, the configuration control set-up, and whether or not it was successful and to convince people—that it was something to be investigated, reported, suggestions made to other design teams in the future and how they might set up their processes to have the same degree of confidence.

- **Man rating flight software**
- **Configuration control processes**
- **Model fidelity requirements**

Figure 9. Verification and validation.

The final item on this list is how much fidelity was needed in the simulations. We ended up with a decommissioned F-8, an iron-bird simulation, where we had a complete set of hardware, the actuators, the hydraulics, the electrical system, and the flight computers. We found it was important and helpful to have the ultimate in fidelity in our modeling before you go to flight.

The arguments on why you really needed to fly the DFBW system (fig. 10) were that by flying it, it forced you to go through all the steps to convince yourself; just going through analysis alone would not be convincing to us or to others. You really had to live it and interact with all the various disciplines—the safety office, the pilots—you've got to go through it, interact, and learn as you go. Out of that comes the understanding of the real operational issues that are important.

- **Only flight forces all problems to be worked**
 - **Operational issues**
 - **Real environmental effects**
 - **Pilot-vehicle effects**
- **Identify the unknowns**

Figure 10. The arguments for flight.

The real environmental effects were more the questions: did you model things right, did you get all the important aerodynamics correct, are there other factors, vibrations, electromagnetic interference (EMI), things that might be out there but did not get into your laboratory model and that you could only get through flying?

The pilot-vehicle effects: of all the PIOs that Mac showed, we didn't know whether we had answered our questions until we went out and flew it and looked at some of the system delays. Again, we had to

identify those unknowns because we had no other way of even guessing that they were there until we flew it.

The changes in thinking (fig. 11) - how do cultures change - we saw it change as we went through the F-8 Program. The attitude that control systems and electronics are like black boxes, in that you expect a certain output from a certain input—that really had to change as we thought about a digital system because it's all dependent upon what that software was doing, and to help people who are not that familiar with digital computers through the process of understanding and gaining confidence that “yes, this is something that I can depend on as well.”

- **The black box approach to flight control electronics**
- **Design and analysis tools**
- **Pilot interface becomes more of a design option**

Figure 11. Changes in thinking.

The design and analysis tools go back to whether it was a Z plane or an S plane. The control law designers had confidence that they had done it right. In some cases they needed new analysis techniques and became comfortable with them; in other cases they decided they didn't need those new techniques.

The pilot interface: what do we display to the pilot? Do we make it as simple as possible? Do we make it simple, but similar to the previous analog control systems interface that the pilots knew or do we do things differently? We discussed those questions with the pilots at length and then entered these concerns into the design. They became important issues as well.

In summary, to hit the main points (fig. 12): The digital fly-by-wire technologies can be broken into two kinds of problems: digital flight control problems and that whole set of learning that came out of the program, and those that are the pure fly-by-wire issues that concerned technology application, and the merger of these two.

- **Digital fly-by-wire technologies opened opportunities and raised issues in two distinct areas:**
 - (1) **Digital flight control**
 - (2) **Fly-by-wire**
- **Redundant digital fly-by-wire promised fault tolerance, but raised generic software error possibility.**
- **Flight offered the possibility to answer these questions, and to provide credibility if actual experience warranted it.**

Figure 12. Summary.

In Phase II, the redundant digital fly-by-wire system had the promise of full fault tolerance, which meant if something fails in the overall system, it could still be counted on to work correctly. Still there was the lingering question of generic software failure and did we need to do anything to insure ourselves that's not in the implementation. Flight offered the opportunity to answer these kinds of questions and we were hopeful that was the right thing to do and was the basis of going on with the program.

Thank you.

CALL TO ORDER

Kenneth J. Szalai

Dwain Deets described the state-of-the-art as it existed at the beginning of the Digital Fly-By-Wire Program and the questions, concerns, and issues which were unanswered, and unknown in some cases. Cal Jarvis was originally scheduled to present the story on what actually happened. Cal is not here today because he is on a NASA Aeronautics "Blue Team" to reexamine the entire NASA Aeronautics Program. Cal was the project manager for the entire F-8 Program until the last couple of years. It turns out there was a conjunction of coincidences that brought Cal to the DFBW Program. He had just completed work on the Lunar Landing Research Vehicle, which was a fly-by-wire vehicle. It was used to prepare the Apollo astronauts for lunar landings.

Before I ask Dwain Deets to return and present Cal's story, I want to point out a couple of things. The electrical and electronic systems of these fly-by-wire aircraft are life critical. I saw Bill Petersen here. Bill is Honeywell trained and also did some flight controls work in Sweden. He brought to this project the skills that were, again, just at the right place and the right time. When we talk about fly-by-wire, we have to ask, "How about the wires?" and Bill brought us that expertise. During this time, there was simultaneous activity going on at NASA Langley to develop some very advanced analytic tools that could model these advanced fly-by-wire systems for use in the design process. Bill Dove was one of the leaders of that activity at Langley for several years. He is also here and we're very happy to see him.

I should also mention that advanced control law work was carried out at Langley under the lead of Jerry Elliott. Ray Montgomery was a key contributor there. They worked for Jay Bird, who has since passed away. One of their bright engineers was Joe Gera, who also worked for Dr. Whitcomb. He transferred to Dryden where he worked on advanced flight controls.

I now reintroduce Dwain Deets, to recount the results of the program.

THE DIGITAL FLY-BY-WIRE PROGRAM

Dwain Deets (for Cal Jarvis)

There were two phases of the F-8 Digital Fly-By-Wire (DFBW) flight research program and toward the end, we broke Phase II into two parts: Phase IIA and IIB (fig. 1).

I'll go over the three phases with the main focus on the first two. Phase I was making use of the Apollo Guidance Computer in a single-string manner; Phase IIA covered the redundant system. Last was Phase IIB, the research test bed.



- | | |
|-------------|---------------------------------|
| • Phase I | Apollo Guidance Computer |
| • Phase IIA | Redundant digital system |
| • Phase IIB | Research test bed |
| • Summary | |

Figure 1. Outline.

Figure 2 shows the generic-sounding program objectives for which we were not sure what to do, given a statement at this level:

- Establish practicality of digital fly-by-wire for conventional aircraft. It's strange that the word "practicality" was used because the system we used was so sophisticated that it really was not a practical system for use in aeronautics. However, we really wanted to use a digital system.
- Assess the applicability of current design tools.
- Find out what level of confidence we could obtain.

Program objectives:

- **Establish practicality of DFBW for conventional aircraft.**
- **Assess applicability of current design tools.**
- **Establish level of confidence.**

Approach:

- **Apollo Guidance Computer**

Time period:

- **1970–1972**

Figure 2. Phase I.

The Apollo Guidance Computer and the other components that went with it such as the inertial measurement unit - using that whole package was the approach.

We did Phase I from 1970 to 1972. Earlier, in 1969, the process of selling this program was amazing because the person who made it happen was Neil Armstrong. He was the associate administrator to the equivalent of what is now the Office of Aeronautics and Space Technology (OAST), which was called OART at the time. What Neil saw was the opportunity to make this technology transfer from space, which he was so much a part of, to aeronautics which was then his responsibility as AA. He thought that it was the right thing to do. Prior to talking to him, as we talked with the various people at the lower levels, there was a universal "NO" response. At least they all said, "Well, why don't you go ahead and talk to the next level?" That contribution was important because they could have said, "No, absolutely not." The people below allowed us to advance the idea and Neil approved it.

As figure 3 shows, there were technical advantages in selecting the Apollo Guidance Computer for this conceptual demonstration. The computer was reliable; in all of the testing that had been done to get ready for Apollo and during all its missions to the Moon there were no failures. We said that the reliability was proven to be greater than 90,000 hours mean time between failures (MTBF) and we are still looking for the first failure to find out what it should be. The existing contracts were the contracts that the Apollo Program had set up, so Draper Lab and AC Spark Plug, organizations that were under contract, could immediately go to work on the F-8 program. The industry teams were very excited about working with us on the F-8.

- **Advantages**
 - **Reliability (> 90,000 hr MTBF)**
 - **Surplus equipment available**
 - **Existing contracts could be utilized**
 - **Software development facilities in place**
 - **Could build on Apollo experience**
- **Disadvantages**
 - **System optimized for different application**
 - **Some limitation on aircraft maneuverability**
 - **Special cooling requirements**

Figure 3. Selection of Apollo Guidance and Navigation System for Phase I.

The software development facilities were in place and I don't think we appreciated the importance of this. We could now see what the code was doing. There were some very sophisticated tools, for that matter, in Draper Lab that allowed us to really understand the inner workings of these computers. We had the Cadillac approach capability, and we found out later how much that capability was needed. After we experienced the knowledge of the people, we found out how important it was.

There were also disadvantages; for example, the system was optimized for a different application using an inertial measurement unit to provide vehicle rates. This was an inertial measurement unit that was designed to measure angular position very accurately in certain regimes—very small changes. The rate measurement accuracy was really quite poor. This imposed limits on aircraft maneuverability because the inertial measurement unit (IMU) could not keep up with the airplane in roll, for example, if the roll rate was greater than 80 deg/sec. The hardware also had special cooling requirements which had to be met. We spent a lot of time making that system work for us.

Under Phase I ground rules (fig. 4), the decision to go with no mechanical reversion was a decision to force us to do everything right. We saw that the long-term possibility was a control-configured vehicle

where we wouldn't have a mechanical control system. We could have pretended that we didn't have one but still have it, in case we needed it. The environment would be, "Well, we're always going to have that as our fall-back position and we're not going to force ourselves to go through the ringer and the convincing arguments that you know that you could reprogram." That decision was made and we broke the mechanical link so there was no capability to revert to a connection between the pilot stick and the control group.

- **No mechanical reversion capability**
- **Simplify pilot's interface with computer**
- **No hardware changes to Apollo GN&C system**

Figure 4. Ground rules for Phase I.

We knew that we needed to simplify the pilot's interface with the computer. The Apollo display turned out to be a nice interface device for engineers, but for a pilot to need to think of these kinds of things flying around in the atmosphere really was not the thing to do.

We needed to figure out what made sense for the pilot interface with the system that was not much different from what the pilot was familiar with, but still had the flexibility to do what we configured it to do. We decided to not allow any hardware changes to the Apollo guidance, navigation, and control system because the integrity and reliability were dependent on the existing hardware. Therefore, we didn't want to make changes because then we had to figure out whether we had compromised the hardware and software reliability and performance.

Why did we select the F-8? As shown in figure 5, it had adequate electrical and hydraulic power. The volume was adequate for installing the Apollo system hardware, and it was easy to disconnect the mechanical system, although we found that when we disconnected it, it left an unusual handling characteristic in the stick—a lack of damping. The flight envelope was quite broad, and it was flyable without controls augmentation. We thought that it was an advantage because it turned out that the feedback sensors were not working. The availability of an iron bird, a separate airplane, a decommissioned F-8, we thought was also important - we did have one - so that seemed to be the right thing.

- **Adequate electrical and hydraulic power**
- **Volume for system components**
- **Mechanical flight controls easily removable**
- **Broad flight envelope capability**
- **Flyable without control augmentation**
- **Availability of decommissioned F-8 to serve as "iron bird"**

Figure 5. Reasons for F-8 aircraft selection as test bed.

When Cal was running through these figures with me, I thought an important consideration, not on this list, was that the F-8 had an ejection seat. Had it not had an ejection seat, we probably would not have proceeded with this airplane selection.

This is the system architecture diagram (fig. 6). The primary system is in the upper two-thirds or three-quarters of the figure and then the back-up system is on the bottom. The first half of the primary system

was single channel, as I've mentioned. From the Apollo computer onward, we had a dual channel system from there on. One channel was an active channel, and one was a monitor. We didn't worry about reliability problems with the hardware that we added to get the signal to the control surfaces. We had this secondary actuator that Hydraulic Research and Manufacturing built for us. They connected to the power actuator at the point that the cables would have connected.

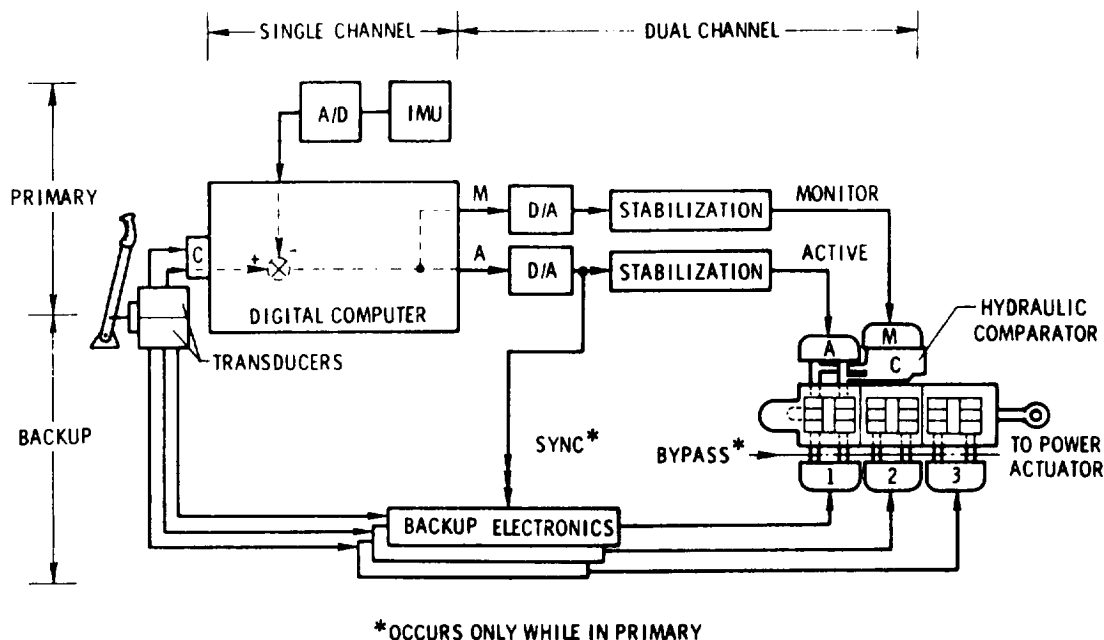


Figure 6. F-8 system architecture, Phase I.

Part of the problem was synchronizing the primary system with the back up so any time we had to revert to it, we would have a known status of the back up and would be tracking reasonably well with the primaries. We worried over that sync and how it got into the back-up computers. It's a jump now to the summary of Phase I.

Figure 7 summarizes Phase I flight results. From the first flight in May 1972 through November 1973 we made 42 research flights with six pilots. The key finding that I would tell other people was that the existing control design tools were adequate for that job. We didn't have to develop or invent anything.

• Flight program	May '72-Nov. '73
• Total flight hr	58
• Total flights	42
• Number of pilots	6

Key findings

- Existing control law design tools adequate
- Software development tools critical to establishing confidence in system
- No software programming errors found in operational system
- Functional changes late in decision cycle possible without impacting hardware schedule
- Verification of flight critical software requires extensive effort

Figure 7. Phase I - flight test summary.

The software development tools particularly and the environment at Draper Lab were critical to understanding what was going on within the digital system. We found no programming errors in the operational systems software. We had done an excellent job of reviewing the verification and validation (V & V) leading up to the flight. We did make some functional changes late in the design cycle without really impacting any hardware schedules. Those are all important pieces of information to come out of the experience. It was not so much a system, but the whole approach—the people, how you went about doing the program.

Figure 8 outlines Phase IIA. The first program objective was to establish a design base for a practical DFBW system. Next was to assess application of advanced control laws which we—the thought of having powerful digital computers—control law designers had all kinds of ideas of what we might do with that computer power in the airplane to make your control laws do things that never would've been possible in the past.

Program objectives:

- **Establish a design base for practical DFBW**
- **Assess application of advanced control laws**
- **Support shuttle system development**

Approach:

- **Redundant (triplex) general-purpose flight computers**

Time period:

- **1973–1978**

Figure 8. Phase IIA.

Our work in the F-8 Program gave us the ability to help the Space Shuttle Program as they were developing their system. Both programs were using the same flight computers and we were able to exchange information from our respective programs.

We ended up with triplex general purpose flight computers from IBM—the AB101.

Figure 9 shows how we thought we were going to do it, where we had done the Phase I single channel system. There was also the cost, \$7.6 million and that was the delta cost because so much was already available from the Apollo infrastructure. We had the actual dollars to make the application to the F-8.

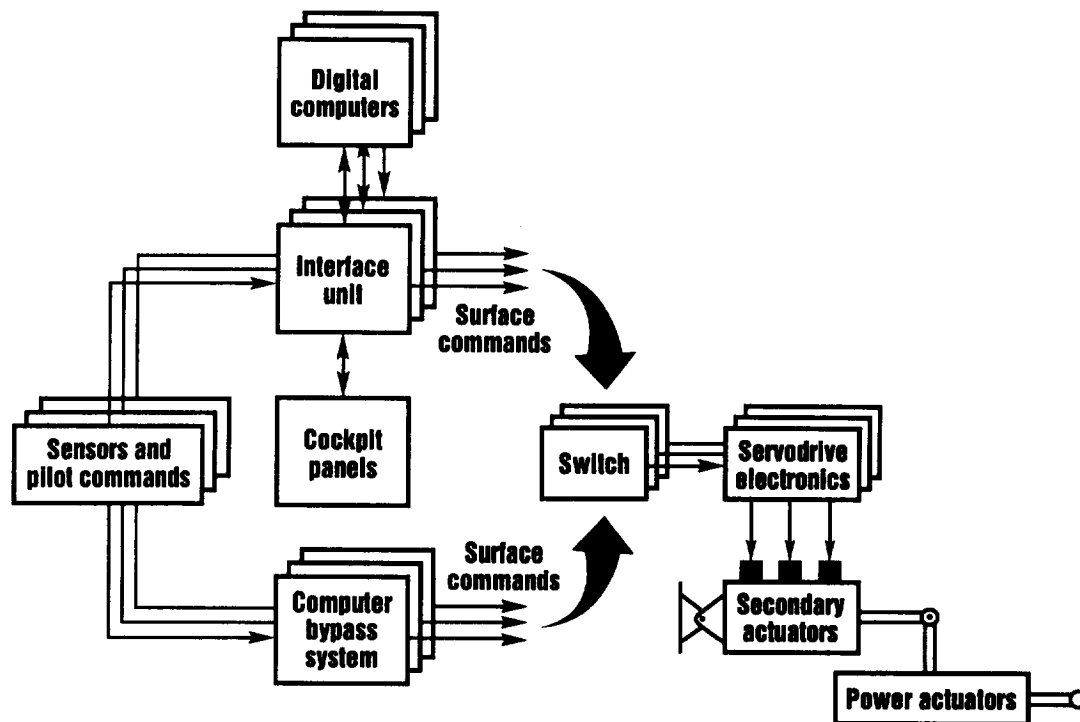


Figure 9. F-8 system architecture - Phase II.

Then the question was, “Well, what should we do next?” The debate was whether we could lick all the problems just with two digital computers, and we had to assume that we had gotten down to our last two. Whatever the number of channels we initially had, when there were two left, we would say, “Well, now what do we do?” That was one approach. If we did that, then when we got down to the last two, the trade-offs are we got two more powerful digital computers and work some of the more advanced control law schemes, instead of working with redundancy aspects and communication between channels. When the Shuttle Program needed answers in this area, it was clear that we also needed to be working these redundancy management questions. The Shuttle Program had to have confidence they were doing it right, so it was obvious that we had to go to a triplex system with multiple communication channels.

The system architecture for Phase II—as you can see, there was three of everything. The interface unit was a sophisticated piece of hardware. Often we focused on the computer itself and what it could do. The interface and the ability to be highly tailored is important, too.

The back-up system was the same as before, no change was made. We were able to go into the secondary actuator servos - I’m not sure if it was a \$1 million switch or a \$15 million switch. That device allowed us to switch between the primary and back-up system under any kind of condition that you can imagine, confidently, with high integrity, and that’s much more challenging than a diagram on a chart would suggest.

Figure 10 provides some meaningful numbers. For example, the Apollo LEM Computer was compared with a current date computer. Those were the kinds of dramatic improvements that we dealt with, so you can imagine the kinds of problems that we faced.

	Phase I	Phase II	Current SOA
	<u>Apollo LEM Computer</u>	<u>IBM AP-101</u>	<u>1750A</u>
• Memory cycle time (microsec)	11.7	0.9	0.05
• Fixed point multiply (microsec)	46.8	4.8	0.75
• Main memory size (K words)	37	32	96
• Word size (bits)	16	32	16
• Fixed or floating point arithmetic	Fixed	Floating & fixed	Floating & fixed
• Memory types	ROM	RAM, ROM	RAM, ROM, EPROM

Figure 10. Comparison of flight computer characteristics.

Figure 11 is a time history of F-8 system software discrepancies. We didn't just measure performance of this system, we had to be introspective when we did the system development. We looked for those parameters, and some of them were already known within the industry, which shows how things were going. These were documented accumulated software anomalies, because every time there was a software anomaly you wrote up a discrepancy report, so at least you had something that you could measure and show the build up. The report was broken down into serious anomalies and all anomalies - I've seen other reports that showed software anomalies and hardware anomalies to show how things were going before you had your first flight. As time went on, you stopped having this increasing rate of anomalies, and the numbers came at a more regular pace because every day you'd find another anomaly. A leveling off of the discrepancy curve was an indicator of system maturity. This kind of information ended up being important to designers as well.

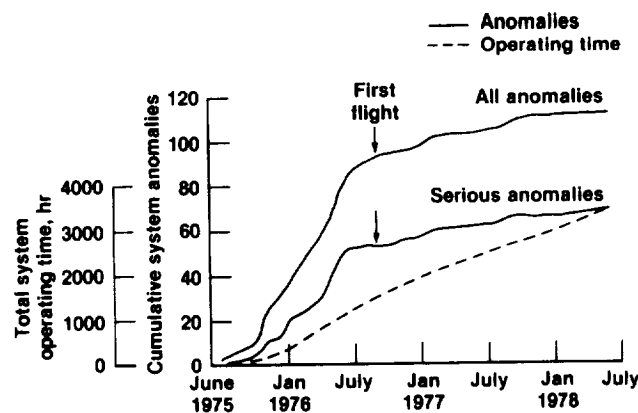


Figure 11. F-8 DFBW system anomaly experience.

Figure 12 summarizes results from Phase IIA. There were approximately the same number of flights as in Phase I, plus a few more pilots. Toward the end we had a number of guest pilots that were brought into the program. With these findings, we document a high-integrity DFBW system without nuisance trips, where you had redundant systems, a frame-synchronized system as this was. It turned out the computer failure rates were higher than predicted, and we ended up having 4 failures in flight during that 55 hours.

The system, however, responded exactly as it was supposed to when these failures occurred, reconfiguring itself, voting out channels, for example with no control transients. The integrity of the total system was demonstrated.

- **Number of flights** **54**
 - **Total flight time** **55 hr**
 - **Envelope** **(1.2 M, 40 K ft, 6 g)**
 - **Number of pilots** **11**
- Key findings**
- **Frame-synchronization between redundant channels provides high integrity without nuisance miscompares**
 - **Computer failure rates higher than predicted, but redundant system reconfigured with no transients**
 - **Hardware and software configuration control is facilitated by establishing similar processes**
 - **Shuttle flight hardware and software validated through flight test experience**

Figure 12. Phase IIA - flight test summary.

Hardware and software configuration control was facilitated by establishing similar processes. We had hardware configuration control that had been used for years at Dryden, and everyone understood what worked and how we did it. The Space Shuttle flight hardware had essentially the same computers. In some cases, the modular software that would fly in the Shuttle, we flew in the F-8 in the same environment.

Figure 13 is an overview of the DFBW test bed operations. There was a lot of control law work, quite a range of experiments. Langley was heavily involved in some of those concepts and the F-8 allowed them to get into flight. Several universities had grants and ended up with concepts that could be evaluated. We developed a remote control system augmentation facility with which we could uplink commands and receive downlinked F-8 responses while investigating experimental control system and software designs in the laboratory environment.

Objective:

Research test bed for advanced control concepts

Example experiments:

- **Advanced control law concepts**
 - **NASA (Langley and Dryden)**
 - **Universities**
 - **Contractors**
- **Time delay effects on flying qualities**
- **Resident back up software (REBUS) concept**
- **Cooperative (NASA and RAE) advanced digital research experiment (CADRE)**

Time period:

1978 - 1985

Figure 13. Phase IIB.

The investigation of time delay effects on flying qualities and the resultant PIO was not to show that the pilot couldn't handle it; we were investigating what the maximum time delay was that a pilot could fly with. We were systematically adding even additional delays (more than the system itself normally had) to find the limit.

The resident back-up software allowed you to transfer to different software if you had a failure, such as a detected failure in the primary system. The software would be in separate memory but still within the primary system.

In a cooperative program with the Royal Aircraft Establishment (U.K.), the F-8 test bed was used to facilitate some of their advanced digital control systems research.

Figure 14 is a short summary. The Phase I used the Apollo system which was a reliable system that allowed us to get going and learn. Phase II used the commercial-grade computers (off the shelf), and allowed us to find out what kind of redundancy our DFBW system had. Finally, much of our outputs were the processes and procedures and how they led to a system with which we had high confidence in its integrity and qualification as "man-rated."

- **Phase I utilized Apollo GN&C team and equipment to gain a running start on fly-by-wire for aeronautics**
- **Phase II emphasized commercial-grade computers and redundancy concepts**
- **Much of the output was in processes and procedures that led to high confidence in integrity of the system**

Figure 14. Summary.

Thank you.

INTRODUCTION OF GARY KRIER

Ken Hodge

Having heard all of the preceding we now turn to one of our research pilots to give you the pilot's impression of the fly-by-wire.

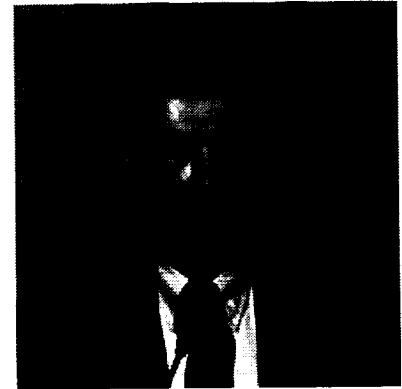
The speaker will be Gary Krier, who started his flying career in the Air Force and joined NASA Dryden as a research pilot almost 25 years ago to the day. He made the first flight of the digital fly-by-wire airplane; he was the project pilot. He also served as the co-project pilot on the Supercritical Wing Program of which we'll hear more this afternoon. In the mid-1980's he obtained a law degree and went to work in the Ames Chief Counsel's office at Moffett Field. He left Ames to go to NASA headquarters, where he worked in the Aircraft Management Office and in the Space Shuttle Office. He is currently in the Office of Space Systems Development helping NASA develop an advanced launch system. At this point, I want to introduce Gary Krier.

A PILOT'S VIEW OF FLY-BY-WIRE

Gary Krier

Well, I'm Gary Krier, but you can call me Geraldo because I've got a couple of really great war stories to tell you. Now it can be told!

Let me start out by saying that I was sitting in the pilots' office one day in the other building and Bruce Peterson came in and said to me, "I just got a phone call from Phil Oestricher, who is down in Fort Worth and they're building this new airplane, the YF-16, and they would like you to come down and fly the simulator, a couple of NASA guys." So Bruce and I jumped in a T-33 and flew down to Ft. Worth to fly this simulator. On the way down we're talking back and forth and said, "Why do they want us to do it?" It turned out that Jerry Gentry, when he was in the Air Force and was here, went down to fly the simulator and they wouldn't tell us the results. Phil was absolutely pristine about saying, "Well, just come down and fly, you know, we just want some other opinions." So, Bruce gets in the simulator first, they knew him very well and besides that he was a Marine (he goes first, the Point Man!), he flies the airplane and I'm sitting outside (keep in mind that this is just a simulator - this is the first time that they've done their control laws and phasing). Bruce gets real red in the face, then the blood begins to drain from his face, it turns really white, and he completes his evaluation and says "thanks."



I get into the simulator and fly it and I'm having a terrible time with it. The thing that I remember, it's funny how these things stick in your mind, I remember what Fitz Fulton said when he was quoting Joe Cotton about one of the airplanes, I don't remember if it was the first flight of the B-70 or whether it was one of the first flights of the B-58. But Joe Cotton said on the powered approach configuration, "Well, it's all right I guess, if your task is to land somewhere in California." So, we go back and Neil Anderson and Phil take us back to Carswell AFB—they're both on the ladder after we're in the airplane and they're saying, "Thanks guys, for coming down here and flying this thing. We really appreciate it and wanted to get your opinion." We just didn't know how to convey the message of what we're trying to tell them. So we said, "Ok, what we'll do is Bruce and I will give individual ratings, write a report and send it back to you." So again, flying back I'm saying to Bruce over the intercom, "Bruce, how are we going to handle this thing? I don't know what to say. These people are contractors, we don't want to alienate them, we don't want to over play the thing, but I can't land it!" I mean the gains and the phasing are such that - and they had at the time—it was not a mobile stick, it was a hard force stick with no displacement. So, we talked to Phil afterward, over the telephone, who recognized that we've got a pretty severe problem with the airplane and that's the message we conveyed.

Now I'm going to tell a tale out of school and that is, that what happened was: that's exactly what Phil said; that's exactly what Neil said; that's what Jerry Gentry said. The problem was their previous success, and that was on the F-111 they did an outstanding job on it and the same flight control system engineers said, "All right you guys; look, we've done the job, we did the job on the F-111. Look how this thing flies, it flies beautifully" (which it did). "We don't want to hear this stuff about cut the gains, change the phase and do this and that." So, you saw the results in the film, you saw the PIO, that's what happened to Phil. But my question was, "Why does the film always stop when the airplane is in an attitude like that?" They never showed the pilot putting himself into the loop, becoming part of the system, smoothing it out like

Phil did, and taking the airplane off, coming around and getting integrated with it and making a terrific landing. Because if he hadn't done that, if there were a lesser person in the cockpit either as a pilot or an engineer that knew the systems, that airplane would be in the trash heap today. Phil, I want to congratulate you on what you did and express our appreciation.

The second war story has to do with the famous F-8 PIO and I'll save that for the movie clip.

Twenty years ago plus two days, I and about 200 other guys made the first flight on the F-8 Fly-By-Wire. That occasion was very important to me, and I knew it was an occasion that I'd always remember, so I made some prepared remarks. I still have them today and I'm going to read to you what I said 20 years ago.

"The pilot more than anybody else realizes how hard others have worked. Some persons destroy and others build. I think that all of us who contributed to this project of advanced technology, years from now when fly-by-wire is common and the shuttle makes its return from orbit, we can all reflect on our first digital fly-by-wire airplane. We knew where we were going, we knew what we wanted to do, we could foresee the future and the applications. The pride of ownership has been unparalleled. One example that I can remember is seeing an electrician sanding down the airplane prior to painting it. I don't believe I have seen a better group."

When I first read those remarks, I didn't need glasses, and thanks to Mac computers, large fonts, and large type, I still don't need glasses! (Speaker showed the audience an 8 1/2 X 11 sheet of paper with a large letter A on it).

Now we're going to see a film clip of which you have seen parts already. Let me go over it beforehand, and then after I've done that, we'll run the film clip and you'll get a chance to enjoy it - there's some music on this thing, but I'll try to do minimal voice overs so you can enjoy the film. The film clip shows a pre-flight and it shows some close formation flying which is a good closed-loop task to determine how an airplane is going to behave. In my opinion it is a very good test to see if the airplane PIOs. There's only one problem—you've got to get airborne and up and away before you can do that. If you can't get off the ground safely, you can't test it in formation flight! So that and gunsight tracking are excellent so there's a brief clip to show it—it shows a little pilot porpoising—but not very much. You'll see a little more on the first flight landing which is also in there.

Shuttle transport time - you'll see that again - there's something additional that I want to say about that, to get everybody to relate to what Phil had to do and what some of the other people had to do when you get one of those flight control systems that has a few interesting quirks. Imagine going out to Rosamond, to that race track out there, and somebody gives you a new race car to drive around that track with two things: one, you're catapulted onto the track, and two, somebody's cut two teeth off the steering gear, and they won't tell you which teeth! That's what it's like to get into an airplane that has those characteristics. So understand that and look for it in simulation.

Here's the second war story. When we did this work on the shuttle, I flew the airplane one day—and I think it was something like a 200-msec time delay—and I took the task that Dwain Deets mentioned before and that is, "How much can a pilot tolerate and still land the vehicle?" I have to admit that I modified it just a little bit. I tried to put it down around 2,500 ft down the runway which was where the shuttle was supposed to land. On final approach I absolutely could not control the vehicle. I could control gross pitch attitude, but it was just passing through attitudes. So I didn't even come close to the ground, I recognize

that, but to me it was uncontrollable so I rated it a “ten.” Einar Enevoldson and John Manke took the task and they looked for ways to make sure that they could land the airplane and to find the point where they couldn’t. So what Einar did, and I’m speaking for him now and I’m sure that this is what John Manke did because that’s what John said, was to get an attitude set up where they were pleased with what the airplane was doing and then just letting the airplane fly on to the ground. If you look at the film clip carefully and you look at the elevator you’ll see minimal elevator motion on final approach and touchdown. Where John got in real trouble was when he got back in the loop on the ground and started to make the wave-off. We’re ready for the film, please. (Film was shown).

Comments during “Digital Fly-by-Wire—the F-8 Experience:”

- This is a great airplane. Originally one of the proposals was to use an F-104 since we had a lot of them. Through what really was a total quality management (TQM) process (although we didn’t know it at the time) the choice evolved to selection of the F-8, an excellent choice.
- Up and away! We’ll soon have a close-in shot of some formation flying.
- This is the first landing, on lakebed runway 18. You talk about slower, better, and less expensive: there’s the Aero Commander chase! We had TQM even then.
- A little quantization there—you could have seen it pitching if you were looking for it.
- A great airplane. You could take a full bag of fuel and if you had a problem you could dump fuel and come back for a landing at relatively light weight.
- This is really close-in formation flying, Phase II I think—and Wilt Lock I think you picked out the film—because this is much, much smoother than we could have done otherwise.
- This ground test sequence is self-test on the analog back-up system. I really appreciated the work done on it by Sperry and Wilt Lock and all the other people who helped out. It gave me a great deal of confidence that whatever happened on the digital system we had an excellent analog system to rely upon.
- There’s an enormous speed brake on this airplane—here it’s coming up for landing. As any F-8 pilot will tell you, when you get the gear down the speed brake goes to “trail,” but you can override that feature if you want to and grind off about 8 in. of speed brake when you land!
- Here’s a shot of the shuttle Enterprise on landing, showing the PIO—the pilot is Fred Haise. He’s caught in a real trap—he’s the guy who’s catapulted off the SCA just like the guy on Rosamond racetrack with a couple of teeth missing in the steering.
- There goes the famous PIO on wave-off with John Manke. If you’d looked for elevator motion you’d have seen very little. Who remembers how John got out of this?

What did we learn? Always, I say again, always simulate software changes before you fly them. If you can’t simulate takeoff or landing as well as possible, you’re in for trouble if you’re doing a flight control program or if the flight controls are untested.

A good research tool can take you anywhere—even places you don’t want to go! Approach things carefully. Tasks rated 8 or greater by any pilot should have severe scrutiny by the responsible manager before being reflighted; involve the entire team!

We can (and should) run our own programs. Contractors should support us, not do our work. The F-8 DFBW trained many of our best personnel—and we still have them with us today! They enjoyed every minute of their workday. That's TQM, that's continuous improvement and that was the F-8 Program!

Now we are in the final phase of the F-8 Program. Honoring the machines, the personnel, and the memories. This is in sharp contrast, by the way, with some of today's programs where the phases seem to be:

1. Wild enthusiasm
2. Mild concern
3. Deep despair
4. Search for the guilty
5. Punish the innocent
6. Awards to the non-participants

Now, after having said all that, will you still give me my medallion?

Thank you.

INTRODUCTION OF GARY HARTMANN

Ken Hodge

Our next subject is the effect of digital fly-by-wire on today's aircraft. Presentation will be by Gary Hartmann, who is a Principal Research Fellow at the Honeywell Systems and Research Center in Minneapolis. He has over 25 years experience with Honeywell in a variety of flight navigation and control pursuits. Although most of his applications have been with aircraft, he has also had experience with oil drilling vessels and undersea vehicles. He has participated in control law development for the F-15 and B-2 Bomber which have been tested here at Edwards. Without further ado, Gary Hartmann.

THE F-8 DIGITAL FLY-BY-WIRE INFLUENCE ON TODAY'S AIRCRAFT

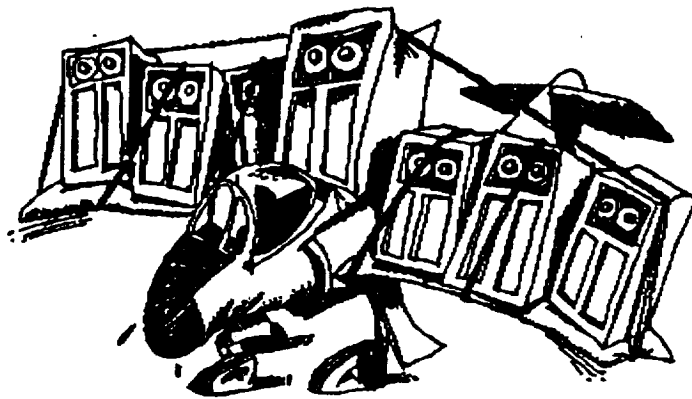
Gary Hartmann

It's my pleasure to come out today and talk about the influences of the F-8 Digital Fly-By-Wire (DFBW) on today's aircraft. What I'd like to do is to give you a perspective from someone in the industry. We're going to talk about how some of the F-8 technology has been applied in other systems, and I'm going to discuss areas where I think it's influenced some of the fly-by-wire activity in the commercial sector.

This cartoon (fig. 1) goes back before the F-8 Program. Some people thought that if you put digital computers in airplanes it would be quite a burden. What the F-8 did was to change that thinking.



Remember me in 1965?



I am digital, I am optimal, I am adaptive, get me off the ground and I will show you.

Figure 1. Progress.

The F-8 was a pioneer in a number of areas; hardware, control laws, redundancy management, and so forth, as shown in figure 2. There were some major contributions made in all of these areas and I'll touch upon them. I think in all of these areas we learned something, and many of these lessons were applied to future aircraft. I also want to emphasize that one of the major benefits of the F-8 was that since the mechanical system was removed, all the fly-by-wire (FBW) problems had to be addressed, we couldn't leave some details off to the side because they were a little messy, or we didn't want to work on them. This perspective had much to do with establishing the credibility of the program and the legacy that's available to future applications.

- **Hardware**
 - **Computer**
 - **Architecture**
- **Control laws**
 - **Active**
 - **Adaptive**
- **Redundancy management**
- **V&V testing**

Figure 2. F-8 Digital Fly-By-Wire—the pioneer.

The hardware for the Space Shuttle was very important (fig. 3). The digital computer hardware matured to a large extent with the F-8 experience. Since the F-8 remained a one-of-a-kind system, there was not a hardware legacy in the sense that the system went into production and was widely used. However, the redundancy management and test approaches are relevant in spite of continuing advances in electronics and computer and language standards. We've moved from HAL and assembly coding to JOVIAL, Pascal, Ada, and other higher order languages. On the computer side we've moved into different kinds of microprocessors. We learned many lessons in redundancy management and testing that are still relevant and, I think, have been successfully applied in other programs.

- **Flight hardware**
 - **Important to Space Shuttle**
 - **Not major legacy to other aircraft**
- **Computers, languages, and standards are dramatically different today**
- **F-8 redundancy management and test approaches still relevant**

Figure 3. Hardware.

One of these involves the lessons learned in synchronizing redundant computers (fig. 4). There is a continuum of approaches. I believe people have made all of the different options work. You can have either clock or instruction synchronization, frame synchronization, or asynchronous applications. As it was pointed out earlier, there's still discussion among designers regarding the pros and cons of different approaches. Certainly the frame synchronous approach that was demonstrated with the F-8 has been used on many other airplanes like the F-18, X-29, X-31, and various helicopter applications. Even though the frame synchronous approach was very successful, there are also operational asynchronous systems such as the F-16, as well as the Swedish Grippen. As I'll discuss later, in the commercial transport arena, we're starting to see increased interest in asynchronous designs as well as issues of generic faults if you have identical channels.

- **Three broad approaches** **Clock**
 Frame
 Asynchronous
- **F-8 DFBW - synch of each 20 msec frame**
- **Similar approaches used on Jaguar DFBW, F-18, X-29, C-130 high-technology test bed (HTTB), X-31, C-17, B-2 ...**
- **However, there are proponents of asynchronous channels**
 - **Military (F-16 C/D, JAS-39 ...)**
 - **Commercial transports**

Figure 4. Synchronization of redundant computers.

One thing that hasn't been mentioned was the F-8 lightning and susceptibility testing (fig. 5). There was much work done with the F-8 looking at the effects of lightning-induced voltages. This work benefited the Space Shuttle as well as the F-16 and F-18. Today this area is of interest to all fly-by-wire applications and in fact, the whole arena of electromagnetic interference (EMI) and high-intensity radio frequencies (HIRF) is continuing to receive a lot of attention. Today as people continue to get better at modeling, they try to reduce the need for testing, but testing is still critical to system verification. In this area the F-8 was certainly one of the pioneers as well.

- **F-8 DFBW demonstrated a non-destructive method for determining the level of lightning-induced voltages in electrical circuits.**
- **This methodology has been used for susceptibility testing of Space Shuttle, F-16, and F-18 fly-by-wire systems.**

Figure 5. Lightning susceptibility tests.

The advanced control work in the second phase involved a number of contractors and universities looking at various control law designs (fig. 6). As Ken Szalai mentioned, one of the legacies we see here is that the F-8 involved a number of young engineers in their formative years when they were in graduate school. They were able to learn modeling and control from these design activities. I'd like to make a few comments regarding three of the concepts that were flight tested as part of Phase IIB.

- **Various studies supported advanced concepts**
- **Contractors/universities included:**
 - **MIT**
 - **RPI**
 - **College Univ. of NY**
 - **William and Mary**
 - **Virginia Polytechnic**
 - **Honeywell***
 - **Draper Lab***
- ***Concepts flight tested**

Figure 6. Advanced control law concepts.

The active control laws experiments (fig. 7) looked at performance and integration of a number of different control functions. It had a multi-mode structure and used a command augmentation system, which means commanding particular response variables of interest as opposed to just damping some of the surfaces. It also had a mode that commanded the symmetric flaps which generated a modest amount of direct lift. The designs were accomplished with linear quadratic control theory and we used explicit models to enforce desired handling qualities. The gain scheduling used dynamic pressure and angle of attack. This was a successful application of linear quadratic theory. One lesson learned was the benefit of looking at optimal control designs in the frequency domain. This led to renewed interest in frequency domain analysis. Even though the details may vary from airplane to airplane, this control structure has been applied to many different military and commercial flight control systems.

Investigate performance and integration of projected active control functions

- **Multi-mode structure**
- **Command augmentation system**
- **Boundary controller (angle-of-attack limiter)**
- **Autopilot functions**
- **Ride smoothing system/maneuver flaps**
- **Gain schedule with airdata**
 - **Industry standard used in large number of military and commercial designs.**

Figure 7. “Active” control laws.

The adaptive control laws (fig. 8) experiments were conducted using Dryden’s ground computer facility. This was an interesting experiment. The maximum likelihood theory had been used extensively in off-line parameter identification. The idea that Dr. Stein had was to use a number of Kalman filter channels to cover the F-8’s operating envelope. I believe we had five of them; four for subsonic parameter tracking and one for supersonic. We estimated surface effectiveness and the pitching moment caused by angle of attack. One thing we learned was that there’s a fundamental need for excitation. We quickly discovered, when the test signals were large enough to get accurate identification, the pilot tended to notice it and thought he was flying in continuous turbulence. This work also pointed out some of the theoretical limitations of adaptive control concerning how many parameters to extract and what to do about model mismatches. This led to a renewed interest in robust adaptive control theory. We have seen some applications to missiles where an airdata system isn’t on board, and there aren’t any pilot concerns about test signals. It is also interesting to note that we haven’t put adaptive control in a production airplane since the F-111. Gain scheduling has become the standard.

- **Use modern identification theory to estimate aircraft parameters for adaptive gain scheduling**
 - **Maximum likelihood estimation**
 - **Estimate dynamic pressure and angle of attack**
 - **Identification algorithm on ground computer**
- **Fundamental need for excitation**
- **Theoretical limitations (uncertainties)**
 - **New robust adaptive theory**
 - **Missile applications**

Figure 8. “Adaptive” control laws.

The final F-8 flight experiment looked at analytical redundancy, which uses the dynamic relations to estimate sensor outputs from dissimilar sensors (fig. 9). There were similar flight experiments done on the A-7 Digitac about the same time. Some performance factors were established, particularly the need for both high-fidelity models and a need for excitation. In spite of these limitations, various forms of analytical redundancy have been used in a number of airplanes, an example is the digital upgrade of the SR-71. A Kalman filter format has also found application in a variety of health monitoring applications for flight and propulsion systems.

- **Estimate sensor output from dissimilar unfailed sensors**
- **Use kinematic and dynamic relations**
- **AR algorithms implemented in parallel with baseline FDIR**
- **Performance factors**
 - **Model fidelity**
 - **Excitation levels**
- **Various forms of AR used in RM and health monitoring algorithms**

Figure 9. Analytical redundancy (AR).

One area that is particularly relevant to some of today's aircraft programs involves fault testing. Figure 10 shows data I took from one of Cal Jarvis' papers that illustrates how heavily the F-8 Program used the Iron Bird Facility - and the rigorous set of test cases used. Today's aircraft systems follow a similar approach. If we look at what happened, there was more automation in terms of being able to run through test cases more quickly, and with the computer power we have now there are larger databases.

- **F-8 DFBW relied on Iron Bird facility**
 - **98% of software verification**
 - **90% of failure modes and effects analysis (FMEA) demonstration**
- **A rigorous matrix of test cases used**
- **Today's testing of DFBW aircraft follow a similar approach**
 - **More automation**
 - **Larger databases**

Figure 10. Flight qualification testing process.

Consider one of the recent examples, the X-31, shown in figure 11. I selected this example because the hardware was built by our division in Albuquerque and I have some familiarity with it. The X-31 uses simulation integrated test environment (SITE) which supports automatic fault insertion and logging of results. This process is automated to where it can run over 30,000 tests in less than a day. Today's systems need a methodical test approach as did the F-8. What has happened is technology has allowed us to be more automated, but the essentials had their origin in the F-8 Program.

- **Flight hardware-in-the-loop simulation**
 - **Interconnects flight hardware to nonlinear simulation**
 - **Piloted evaluation of system**
 - **Data extraction**
 - **Fault insertion**
 - **Closed-loop piloted evaluation from actual aircraft cockpit**
 - **System interface checkout**
- **Fully automated system level testing**
 - **30,000 tests rerun within 20 hr**
 - **Failure isolation and verification**

Figure 11. Recent example, X-31 SITE (simulation integrated test environment).

The next topic concerns back-up systems and dissimilar redundancy (fig. 12). Mr. Deets mentioned some of the work on the F-8 analog system. This approach was actually used in other vehicles such as the X-29. The resident software back-up scheme was also mentioned, which has a separate, dedicated portion of memory (fig. 13). This concept of having a resident software back up has been implemented on several different designs, particularly in the F-16 digital system. Military applications have been willing to depend on identical channels. However, in looking at a transition to commercial systems and commercial fly-by-wire, there's a growing interest in dissimilar software and diverse design approaches. In fact, what I see is that the F-8 just scratched the surface of the kinds of things that we're interested in now. Looking through some of the commercial applications of digital fly-by-wire, there is a strong interest in dissimilarity. These systems have channels that have multiple lanes and the lanes have dissimilar processors and dissimilar software.

- **F-8 DFBW used triplex analog bypass (protection against common-mode software failure)**

This approach used in other designs such as AFTI/F-16 and X-29

- **F-8 DFBW conducted experiments using back-up software**
 - **REBUS (resident back-up software)**
 - **Dissimilar software**
 - **Isolated memory**
 - **Transfer criteria**
- (2 of 3 digital channels generate self fail)**

Figure 12. Back-up systems/dissimilar redundancy.

- **Fixed-gain three axis stability augmentation system (SAS)**
- **Asynchronous operation between channels**
- **No interchannel communication**
- **Dedicated sensor inputs for each channel**
- **Mid-value select for actuator command**
- **Minimal pilot/vehicle interface**

This concept implemented in several designs including F-16 C/D.

Figure 13. REBUS characteristics.

If you reflect on some of these applications to commercial transports, the first two items in figure 14 illustrate a conflict. First, you have to get certification, and that involves the FAA as well as the European counterpart, the Joint Airworthiness Authority (JAA). What they're looking for involves significant hardware and software dissimilarity, which is in conflict with the cost of developing the system and the economics of using it. The other trend I see emerging in commercial applications is the ability to dispatch with failed elements. This is not yet standard practice in fly-by-wire systems. In addition to commercial transports, the other area in which we're seeing interest is the potential application of FBW to the business jet. Here, interestingly enough, you don't have the same pay-off as you have in some of the larger airplanes but it gives you a high-tech image which is important in selling the airplanes. I think that in the years ahead we'll see more commercial applications of FBW technology in the large airplanes as well as in the small.

- **Commercial transport applications**
 - **Economics**
 - **Certification (JAA and FAA)**
- **Dispatch with failed elements**
- **A-320 (in service)**
 - 3 spoiler & elevator computers (SEC)**
 - 2 elevator & aileron computers (ELAC)**
 - Each SEC or ELAC has a control channel and a monitor channel with dissimilar m proc and software**
- **B-777 (in development)**
 - 3 channels/3 dissimilar lanes per channel**
- **MD-12**

Figure 14. Future challenges - DFBW dissimilarity.

Let me go to my last slide (fig. 15) and reflect on the process. The F-8 Program was a well run R&D activity. It successfully demonstrated the technology you see flying in other airplanes today. There was involvement with contractors and universities in the R&D phase. It also enhanced the training of people in the government and in industry. Last but not least, I think the people that did most of the work on the F-8, particularly the people here at Dryden, did an excellent job in disseminating results in papers and conferences.

- **Well run R & D**
- **Successful flight demonstrations**
- **Involvement of contractors and universities in the R & D**
- **Dissemination of work through conferences and workshops**

Figure 15. Reflections on the F-8 DFBW "process."

Thank you very much.

INTRODUCTION OF DWAIN DEETS

Ken Hodge

Thank you Gary for that insightful view from the customer's perspective. Dwain would you like to wrap the session up and then we'll proceed across the street? You can lead the procession for the dedication.

DIGITAL FLY-BY-WIRE WRAP UP

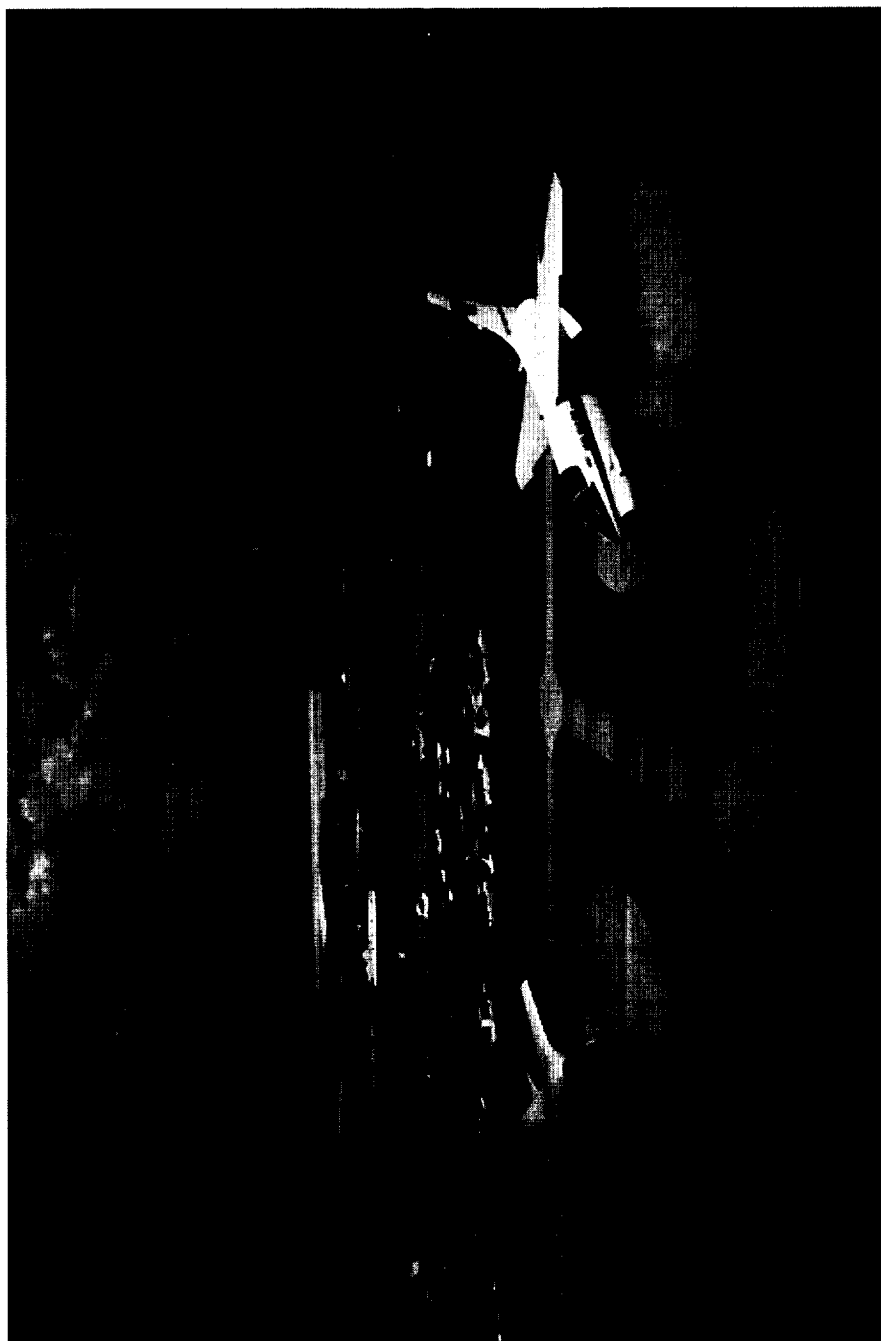
Dwain Deets

I'll make the wrap up brief because more will be said as the dedication proceeds. As I look back at all that's been said, I can either focus on the technologies the program developed and how that happened, or on the people that made it happen. I think it's the latter that is more important. If you look at that group of people - various names come to mind - Ken Szalai's name is the one that stands out because he was a driving force with a strong technical understanding. I also think about the other people working together to make DFBW happen. There was an openness to new ideas; the willingness of the Apollo people to better understand what the aircraft problem was and the Dryden people wanting to understand where the Apollo people were coming from. In addition, there was the crew chief and the people on the floor who wanted to understand these other people's ideas, and finally, the pilots.

Every way you look at it, it was that willingness to develop understanding, and not just taking it at face value, really examining the concepts and technical objectives and thinking it through and letting that be part of their own motivation. Then they explained it to others as well. That really characterizes what happened.

With that I invite you all to head across the street for the F-8 dedication.

F-8 Aircraft Display Dedication



Supercritical Wing (left) and Digital Fly-By-Wire (right)
F-8 research aircraft on display at Dryden

F-8 Aircraft Dedication

A brief outdoor ceremony was held the morning of May 27, 1992, to formally dedicate the F-8 DFBW and SCW research aircraft now on permanent display at the Dryden Flight Research Center. Dryden Director Kenneth J. Szalai greeted attendees and welcomed special guests. Brief welcoming remarks were also provided by Col. Robert Cherry, representing the Air Force Flight Test Center, and by Mr. Richard Kline representing the NASA Headquarters Office of Aeronautics and Space Technology.

Following a summary of program accomplishments, lessons learned, and guidelines for application to future pioneering flight research endeavors, Mr. Szalai cited for special recognition the aircraft ground maintenance teams which supported the two F-8 research aircraft/flight facilities. Present at the ceremony were:

F-8 DFBW Aircraft

Frank Fedor - Assistant Crew Chief

George Nichols

Darrel Sperry

Dave Stoddard

Al White

F-8 SCW Aircraft

Herm Dorr - Crew Chief

Jim Duffield

Danny Garabrant

Darrel Sperry

Jim Wilson

Crew members gathered at the respective bronze plaques as the aircraft on display were dedicated:

DFBW

"This research aircraft was the first airplane to fly using a digital fly-by-wire electronic flight control system, with no mechanical back-up system. The initial system utilized components from the Apollo spacecraft guidance and control system.

"Digital fly-by-wire flight control systems are now being incorporated into the designs of the most modern commercial transport airplanes, and are routinely used on nearly all new military aircraft."

"First flight: May 25, 1972. Pilot: Gary E. Krier."

SCW

"This research aircraft was the first airplane to demonstrate the transonic performance capabilities of a supercritical wing. This airplane demonstrated a drag-rise Mach number of 0.96 at cruise lifting conditions. The resulting technology base permitted an increase in cruise Mach number for transport aircraft from approximately 0.8 to above 0.9. Wings of this type are now routinely utilized on all new military and commercial transport aircraft.

"First Flight: November 20, 1971.* Pilot: Tom C. McMurtry."

*While preparing these proceedings, I discovered that Gremlins in the foundry which cast the SCW plaque had changed the first flight date from March 9, 1971, to November 20, 1971! This clearly shows in the photograph which follows. This latter date was determined to be of no special significance. It is expected that the plaque will have been corrected by the time this CP is in readers' hands. - K.E.H.



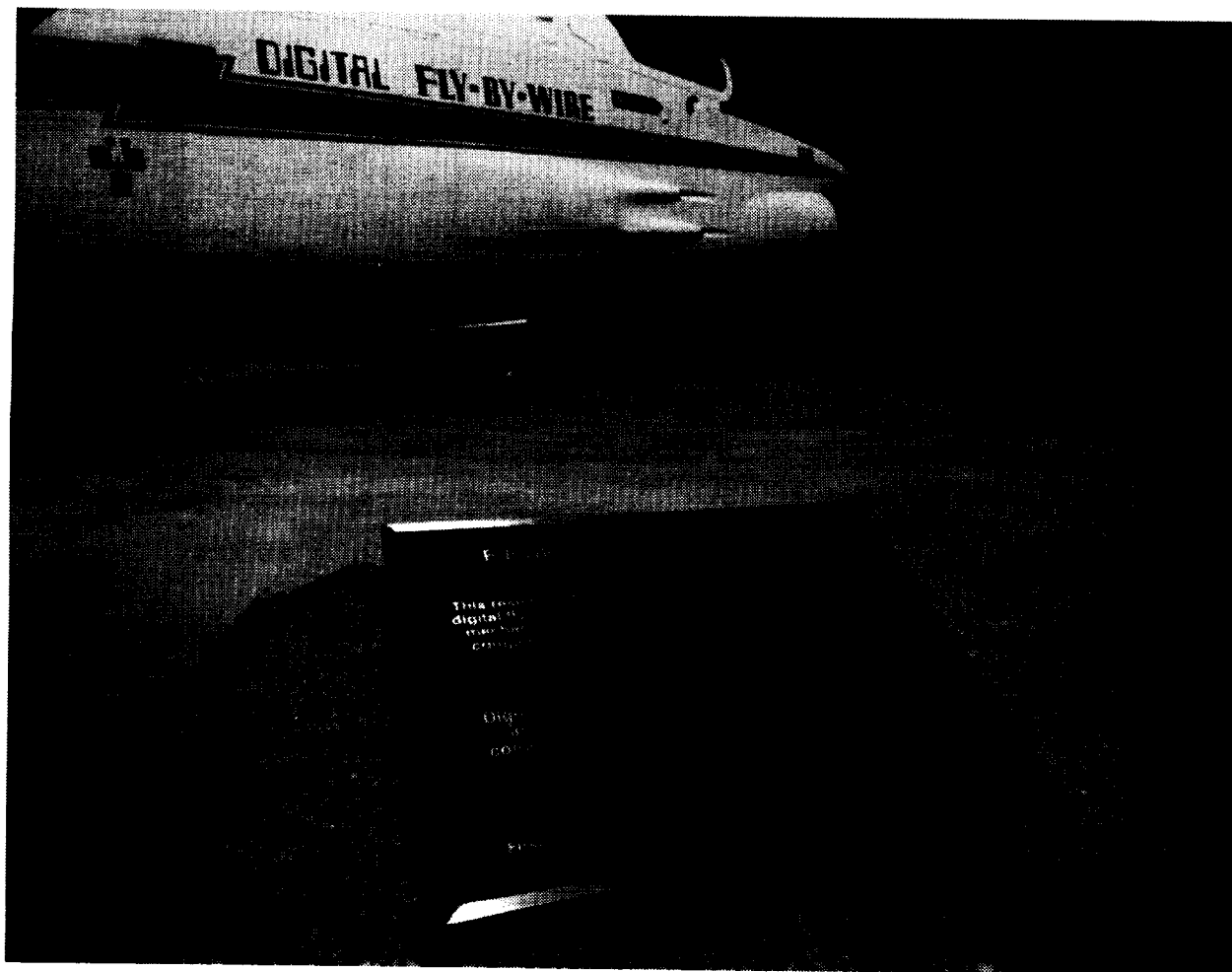
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The ground maintenance crew for the F-8 Digital Fly-By-Wire (from left) Dave Stoddard, George Nichols, Frank Fedor, Al White, and Dan Garrabrant, help dedicate the F-8 DFBW display May 27.

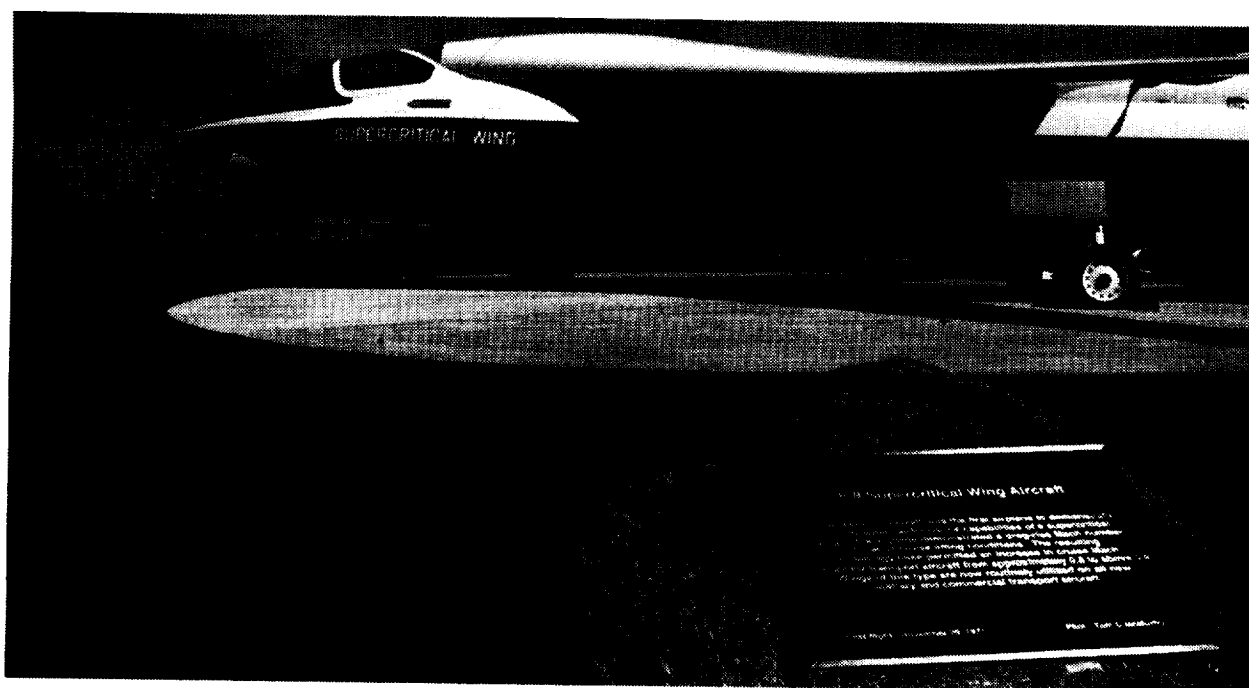


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The ground maintenance crew for the F-8 Supercritical Wing (from left) Darrel Sperry, Jim Duffield, and Dan Garrabrant help dedicate the F-8 Supercritical Wing display.



Digital Fly-by-Wire display plaque.



Supercritical Wing display plaque.

NASA News

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(805) 258-3449

May 22, 1992

NOTE TO EDITORS 92-12: NASA AIRCRAFT DISPLAY DEDICATION

A dedication ceremony to place two of NASA's most historic aircraft on display to the public will be held at the Dryden Flight Research Facility, Edwards, Calif., at 11:45 a.m. on May 27.

Both airplanes are F-8 Crusaders. One was the first aircraft to be flown with a digital fly-by-wire system, now in use on most military aircraft and some civil transports. The other featured the first demonstration of the supercritical wing concept, which is used now by many civil and military aircraft. A symposium with papers on both programs is also being held on May 27 from 8:00 a.m. to 4:00 p.m.

Pilots who flew both aircraft will be at the event, as will local NASA officials.

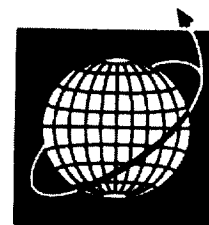
Media planning to cover the dedication and/or the symposium should notify the Dryden Public Affairs Office, (805) 258-3449, by 10:00 a.m. the morning of the event and should plan to be at Dryden by 11:30 a.m. Fact sheets on both aircraft are available, as are photographs.

-end-

NASA Facts

National Aeronautics and
Space Administration
Ames Research Center
Dryden Flight Research Facility
P.O. Box 273
Edwards, California 93523
AC 805-258-3449

International Space Year



ISY

Background

IN THE FIRST FEW DECADES OF FLIGHT, pilots controlled aircraft through direct force — moving control sticks and rudder pedals linked to cables and pushrods that pivoted control surfaces on the wings and tails.

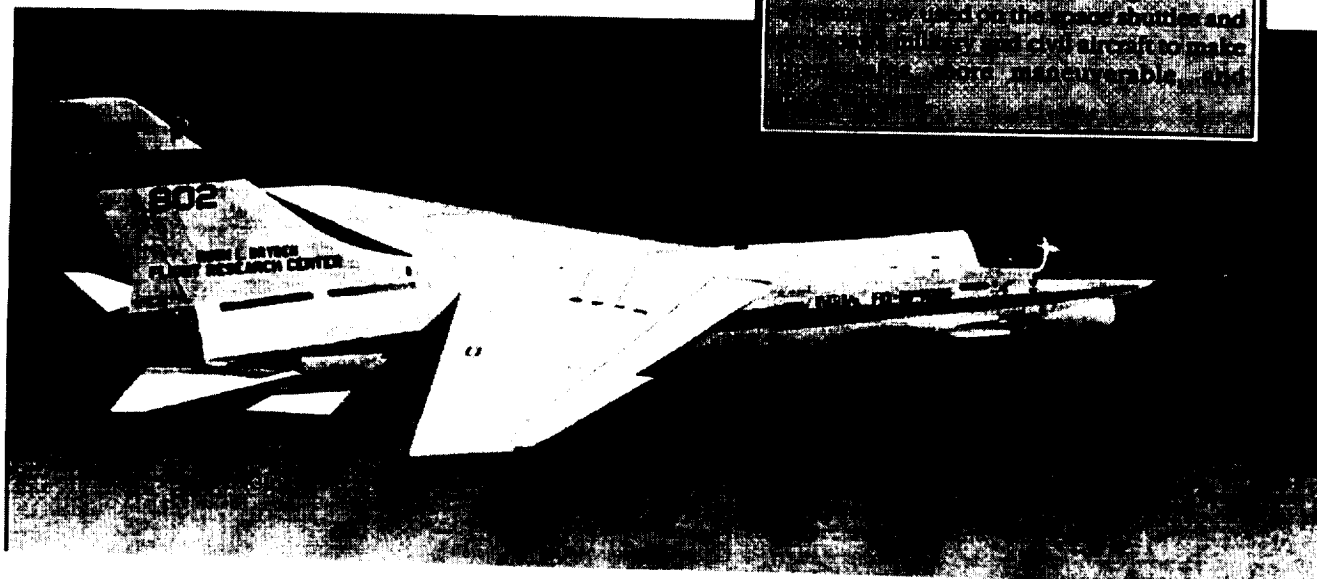
As engine power and speeds increased, more force was needed and hydraulically boosted controls emerged. Soon, all high performance and large aircraft had hydraulic-mechanical flight control systems. These conventional flight control systems restricted designers in the configuration and design of aircraft because of the need for flight stability.

As the electronic era grew in the 1960s, so did the idea of aircraft with electronic flight control systems. Wires replacing cables and pushrods would give designers greater flexibility in configuration and in the size and placement of components such as tail surfaces and wings. A fly-by-wire system would be smaller, more reliable, and in military aircraft the systems would be much less vulnerable to battle damage. A fly-by-wire aircraft would also be much more responsive to pilot control inputs. The result would be more efficient, safer aircraft with improved performance and design.

F-8 Digital Fly-By-Wire

The digital fly-by-wire (DFBW) concept uses an electronic flight control system to replace conventional mechanical flight controls.

The first test of a DFBW system in an aircraft was in 1972 on a modified F-8 at the Dryden Flight Research Facility, Edwards, California. It was the first time that fly-by-wire flight control systems had been used on the space shuttles and would be used on military and civil aircraft to make them more maneuverable and more efficient.



The Aircraft

BY THE LATE 1960s, engineers at Dryden began discussing how to modify an aircraft and create a digital fly-by-wire testbed.

Support for the concept at NASA headquarters came from Neil Armstrong, former research pilot at Dryden. He served in the Office of Advanced Research and Technology following his historic Apollo 11 lunar landing and knew electronic control systems from his days training in and operating the lunar module. Armstrong supported the proposed Dryden project and backed the transfer of an F-8C Crusader from the Navy to NASA to become the Digital Fly-By-Wire (DFBW) research aircraft. It was given the tail number "NASA 802."

The entire mechanical flight control system in the F-8, including all cables and pushrods, was replaced by wires — from the control stick in the cockpit to the control surfaces on the wings and tail surfaces. The heart of the system was an off-the-shelf backup Apollo digital flight control computer and inertial sensing unit which transmitted pilot inputs to the actuators on the control surfaces.

On May 25, 1972, the highly modified F-8 became the first aircraft to fly completely dependent upon an electronic flight control system. The pilot was Gary Krier.

The first phase of the DFBW program validated the fly-by-wire concept and quickly showed that a refined system — especially in large aircraft — would greatly enhance flying qualities by sensing motion changes and applying pilot inputs instantaneously.

The Phase 1 system had a backup fly-by-wire system in the event of a failure in the Apollo computer unit, but it was never necessary to use the backup system in flight.

In a joint program carried out with the Langley Research Center in the second phase of research, the original Apollo system was replaced with a triple redundant digital system. It would provide backup computer capabilities if a failure occurred.

The DFBW program lasted 13 years. The final flight — the 210th of the program — was made April 2, 1983, with Dryden research pilot Ed Schneider at the controls.

Research Benefits

THE DFBW F-8 validated the principal concepts of the all-electric flight control systems now used on nearly all modern high performance aircraft and on military and civilian transports. A DFBW flight control system is also used on the space shuttles.

NASA 802 was the testbed for the sidestick controller used in the F-16 fighter, the first U.S. high performance aircraft with a DFBW system.

Among other electronic milestones first flown on the DFBW F-8 were an angle-of-attack limiter and maneuver-driven flaps, features commonly used on today's new generation of aircraft.

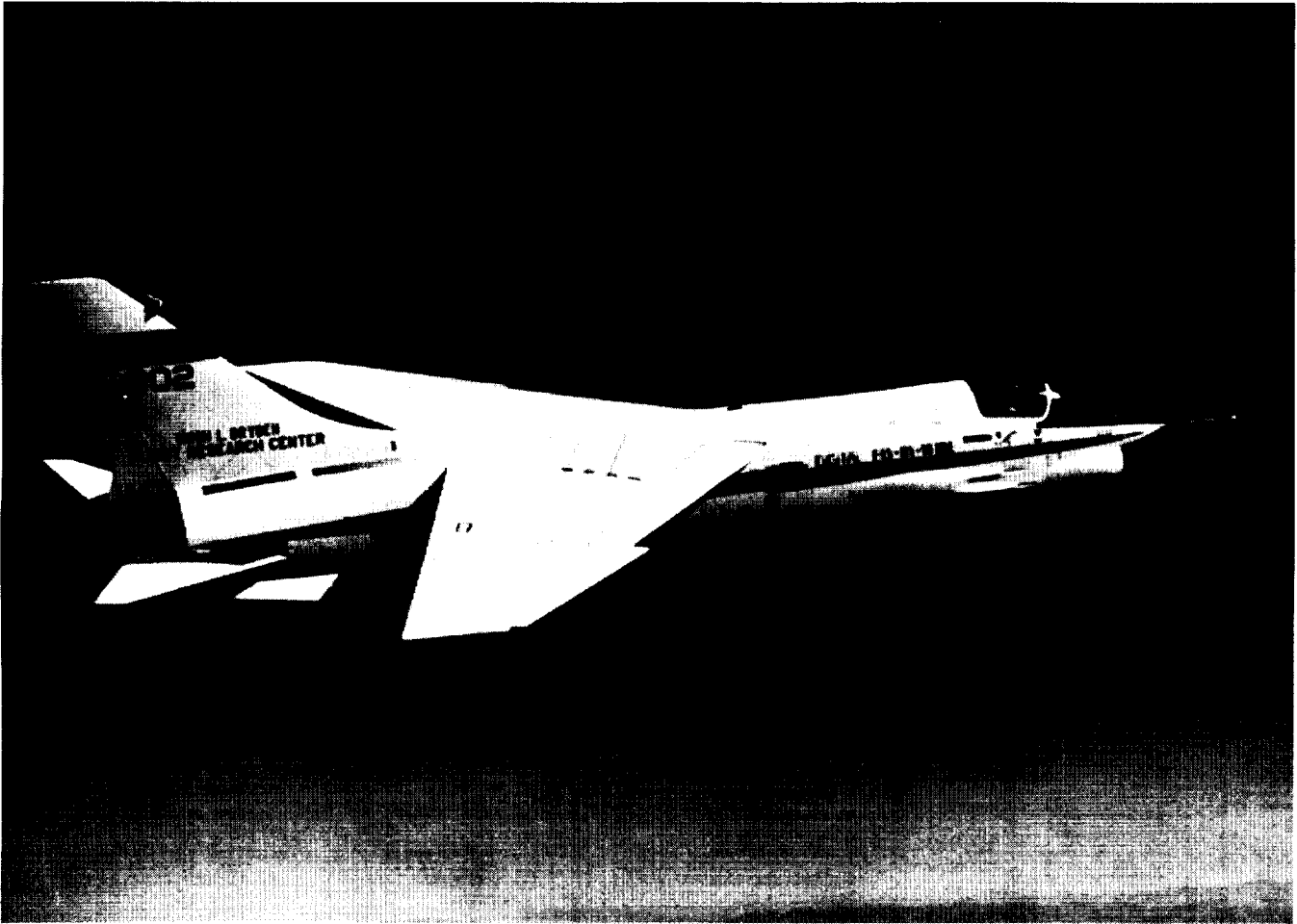
In addition to pioneering the space shuttle's fly-by-wire flight control system, NASA 802 was the testbed that explored Pilot Induced Oscillations (PIO) and validated methods to suppress them. PIOs occur when a pilot overcontrols an aircraft and a sustained oscillation results. On the last of five free flights of the prototype space shuttle Enterprise during approach and landing tests in 1977, a PIO developed as the vehicle settled onto the runway. The problem was duplicated with the DFBW F-8 and a series of PIO suppression filters were developed and tested on the aircraft for the shuttle program office.

The aircraft was used to develop a concept called Analytic Redundancy Management, in which dynamic and kinematic relations between various dissimilar sensors and measurements are used to detect and isolate sensor failures.

In another series of successful tests, a software back-up system (Resident Backup System) was demonstrated as a means to survive common software faults which could cause all three channels to fail. This system has been subsequently used on many experimental and production aircraft systems.

The Dryden project also worked with the British Royal Aircraft Establishment using the DFBW F-8 to produce ground-based software to use when researchers are investigating flight controls in high-risk flight environments. During contingencies, pilots can disengage the ground control software and switch to backup on-board controls.

DFBW research carried out with NASA 802 at Dryden is now considered one of the most significant and successful aeronautical programs in NASA history.



PIONEERING RESEARCH — NASA's F-8 Digital Fly-By-Wire (DFBW) research aircraft cruises over California's Mojave Desert on one of its pioneering flights in the 1970s that developed the electronic fly-by-wire flight control systems. The concept is now used in many aircraft today, including the space shuttle orbiters. The F-8's conventional flight control system was replaced with a digital electronic system utilizing a computer from an Apollo spacecraft. First flight of the DFBW aircraft was May 25, 1972, by Gary Krier, of NASA's Dryden Flight Research Center, Edwards, California. After initial flight tests were completed, the DFBW F-8 was used to test the prototype fly-by-wire sidestick system used now in F-16 fighters and later tested the computer software for the space shuttle's digital flight control system. The aircraft was also used to test simulated lightning strikes on digital flight control systems. The aircraft was retired from flight status in 1985.

(NASA Photo)

October 1991

NASA Facts

National Aeronautics and
Space Administration
Ames Research Center
Dryden Flight Research Facility
P.O. Box 273
Edwards, California 93523
AC 805-258-3449

International Space Year



Background

IN THE EARLY 1960s, Dr. Richard T. Whitcomb, Chief of the Transonic Aerodynamics Branch, Langley Research Center, Virginia, conducted exploratory research which led to the invention and patent of the NASA Supercritical Airfoil. Compared to a conventional wing, the Supercritical wing is flatter on the top and more round on the bottom with a downward curve at the trailing edge (see illustration). The concept was first studied in the wind tunnel at Langley, before actual research with an aircraft began.

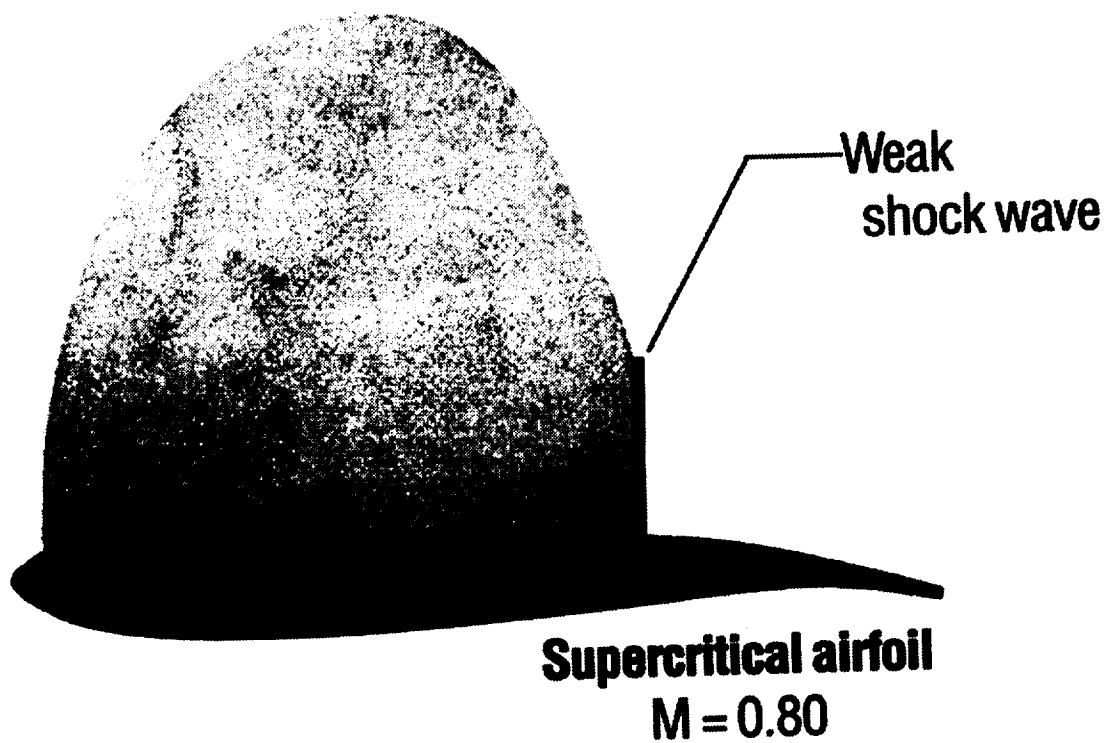
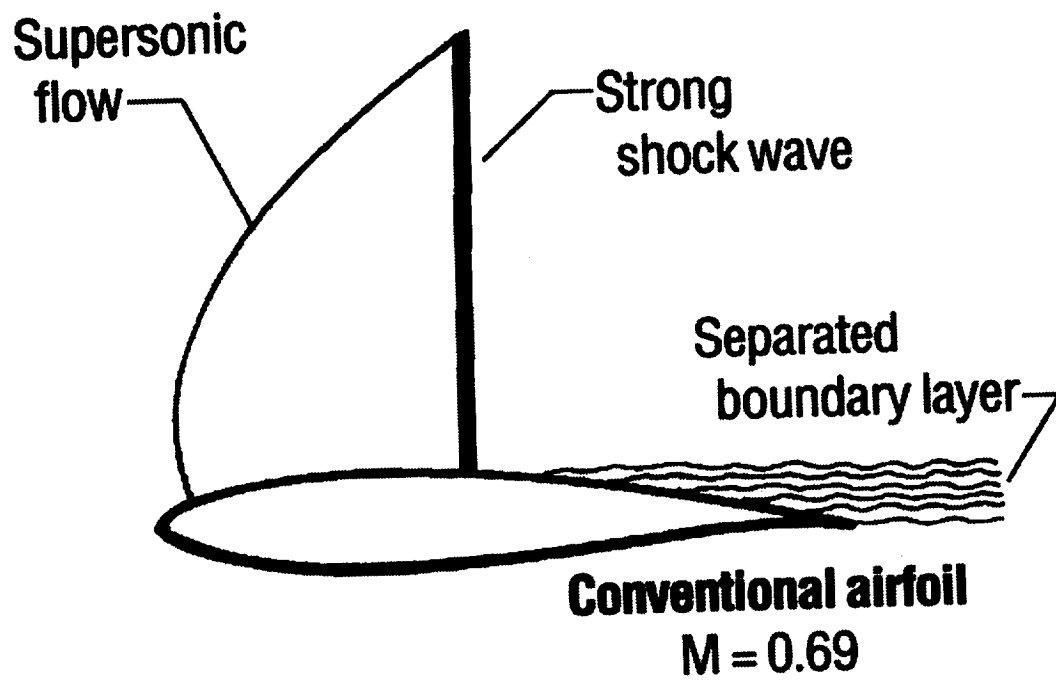
An F-8 Crusader, available from the U.S. Navy, was selected as the SCW testbed. With its easily removable wing, landing gear which retracted into the fuselage and Mach 1.7 capability, it was the perfect choice as a testbed. The announcement that the SCW concept would be flight tested at the Dryden Flight Research Facility, then the Dryden Flight Research Center, was made in February 1969.

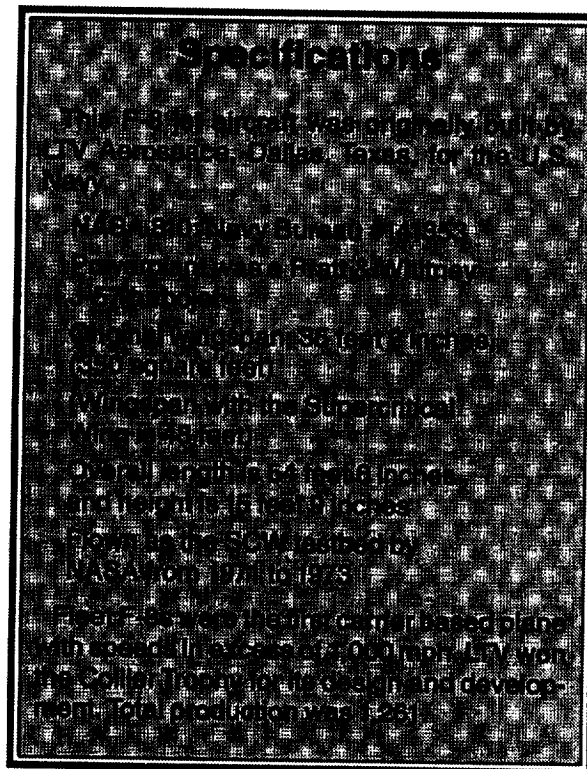
Rockwell International's North American Aircraft Division was awarded the \$1.8 million contract to fabricate the supercritical wing. It was delivered to NASA in December 1969.

F-8 Supercritical Wing

The Supercritical Wing (SCW) was a new tailoring of an airfoil design which delayed the formation and reduced the strength of the shock wave over the wing just below and above the speed of sound. Delaying shock wave formation at these high speeds resulted in less drag. Results of NASA Supercritical Wing research showed that aircraft utilizing the concept would have increased cruising speed, improved fuel efficiency, and greater flight range. Supercritical aerodynamics are now commonplace in virtually every modern subsonic commercial transport design.







Flight Research

DRYDEN ENGINEER JOHN McTIGUE was the first SCW program manager, with Tom McMurtry as the lead project pilot. At Langley, Whitcomb took a personal interest in test results while Thomas Kelly acted as that center's project engineer.

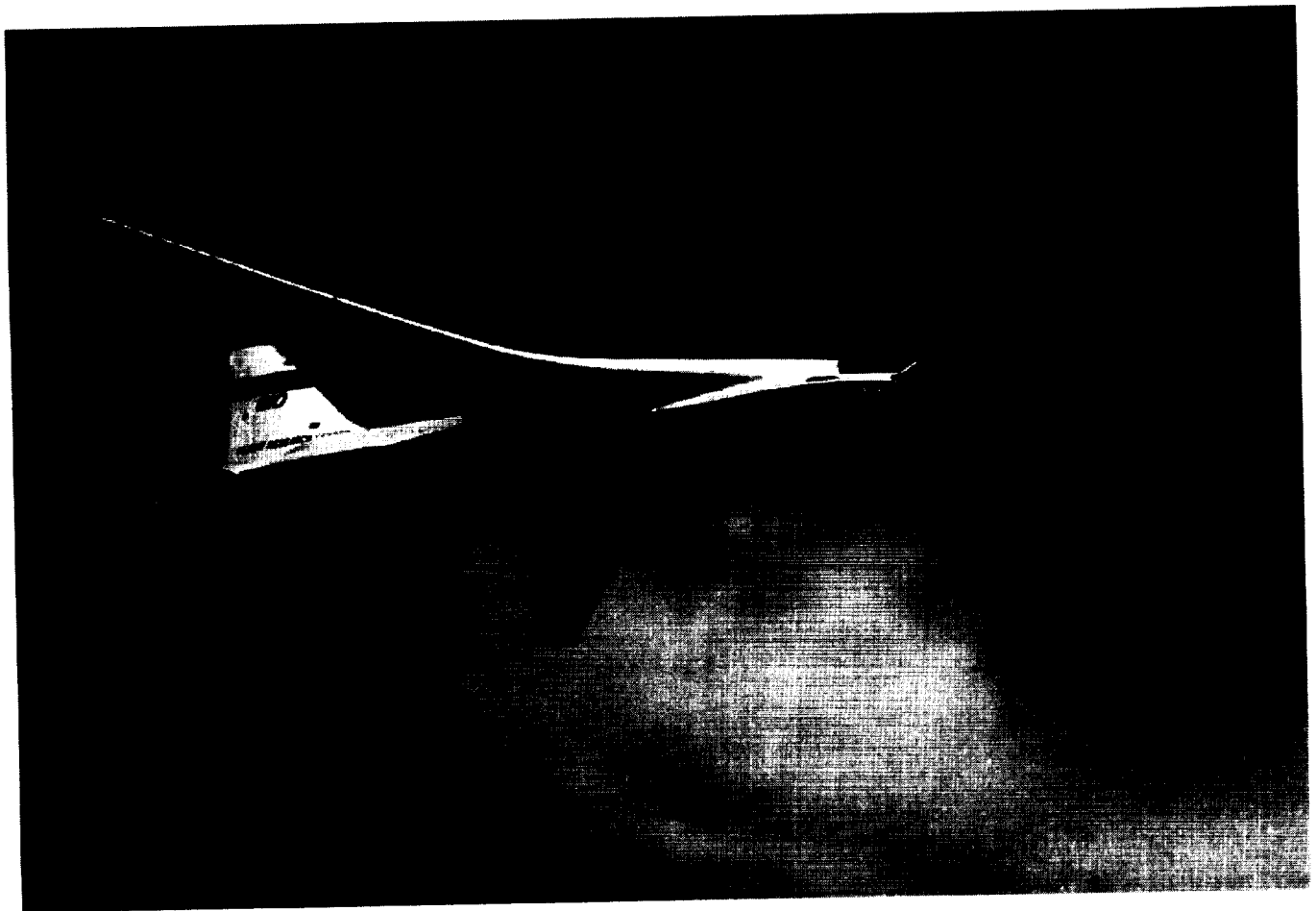
The first SCW flight took place on March 9, 1971, with McMurtry at the controls. On this first flight McMurtry reached an altitude of 3000 meters (9200 feet) and a maximum speed of 300 knots (260 miles per hour).

With the new wing the F-8 landed at a high speed of 230 knots (200 miles per hour). Without antiskid brakes or wing flaps, it was necessary to land the craft directly on Rogers Dry Lake. The 15,000-foot concrete runway at Edwards was used for takeoffs but was too short to accommodate landings. First flight of the supercritical wing at supersonic speeds was on May 26, 1971.

Studies of actual wing performance began in August 1971. Pressure sensors on the wing's upper surface measured shock wave formation. Performance substantiated data from the original wind tunnel tests performed at Langley. In May of 1972, NASA added new instrumentation and installed new fuselage fairings which reduced drag, thereby increasing speed.

Research results showed the SCW had increased the transonic efficiency of the F-8 by as much as 15 percent and proved that passenger transports with supercritical wings could increase profits by 2.5 percent over aircraft with conventional wings. This equated to \$78 million per year (in 1974 dollars) for a 280-plane fleet of 200-passenger airliners.

The last flight of the NASA SCW F-8 was on May 23, 1973, with Ron Gerdes as pilot.



SHAPE OF THE FUTURE — The first supercritical wing to be flight tested on an aircraft appears as a graceful extension to the upper fuselage of a modified F-8 flown by NASA's Dryden Flight Research Center, Edwards, California, from 1971 to 1973. The wing, developed at NASA's Langley Research Center by Richard Whitcomb, features an airfoil flatter on top and more rounded on the bottom than conventional airfoils. Research flights with the wing showed that the supercritical airfoil delayed the formation of the shock wave over the wing at high subsonic speeds, resulting in less drag. This allows the aircraft to cruise farther or faster, with increased payloads, with greater fuel efficiency. Many military and civilian aircraft are now flying with supercritical airfoils.

(NASA Photo)

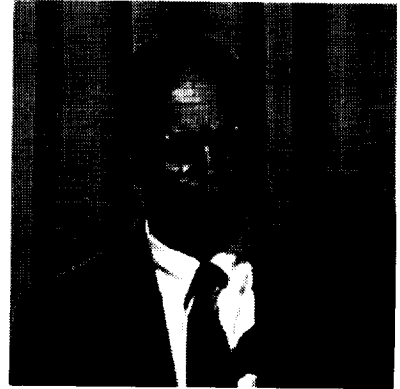
THE F-8 SUPERCRITICAL WING; HARBINGER OF TODAY'S AIRFOIL SHAPES - AND - INTRODUCTION OF DR. RICHARD WHITCOMB

Ted Ayers

Good afternoon, and welcome to the second half of today's symposium. This afternoon we'll focus on the F-8 Supercritical Wing.

As you can see from the title in your agenda, The F-8 Supercritical Wing; Harbinger of Today's Airfoil Shapes is intended to focus on the pioneering aspects of transonic airfoil development. I didn't know what harbinger was until yesterday - I did look it up in the dictionary. For those of you who don't know it, it means pioneering, or apostle, or preceding, or one who changes things.

Up until the mid-1960's the transonic, mixed, or supercritical flow regime was either avoided or viewed with disdain as an environment to be transitioned rapidly or slowly, depending upon thrust minus drag. It was not a very friendly environment to fly into. The first generation of jet transports had gone about as far as they could go aerodynamically in pushing the speed and efficiency of commercial travel.



Dr. Richard Whitcomb, of NASA's Langley Research Center, (characterized by Dick Hallion as saying, "We've done all the easy things, lets do the hard ones") was well aware of this fact and was seeking new challenges. The challenge was great because at this time the state of the art in theory and in ground base testing at near-sonic velocities was very poor. The real tools were intuitive thinking - and I believe here that Dick Whitcomb was world class, perhaps even unmatched—a wind tunnel, and an unlimited supply of auto body putty better known as white lightning or black magic. Just as all good whiskeys, beers, and coffees have their own unique characteristics, so too, does body putty. Taste, smell, texture, and rapid set-up time were critical.

It was this backdrop that set the stage for what was to become several years of intense, and I do mean intense, supercritical aerodynamic research in the Langley Research Center's 8-ft Transonic Pressure Tunnel.

Figure 1 is an artist's concept of the tunnel and I only show it to set the stage of where things took place. The test section is located here; it was a slotted transonic tunnel, capable of speeds from Mach .2 to 1.2 with an additional capability to 1.41. I will leave it to Dr. Whitcomb to lead you through the real story of supercritical aerodynamic research. That research, as we all know today, was important to the future of US competitiveness and was successful as evidenced by its culmination in three flight activities: the T-2C, the F-8 Supercritical Wing, and the F-111 Transonic Aircraft Technology Program (TACT).

There were some aspects of the Supercritical Wing Research Program that are worth mentioning and I believe these are outside of what Dr. Whitcomb will talk about. Whereas the objective was the achievement of efficient near-sonic cruise flight, many other firsts were achieved during the course of this research. It's these other things that I would like to focus on.

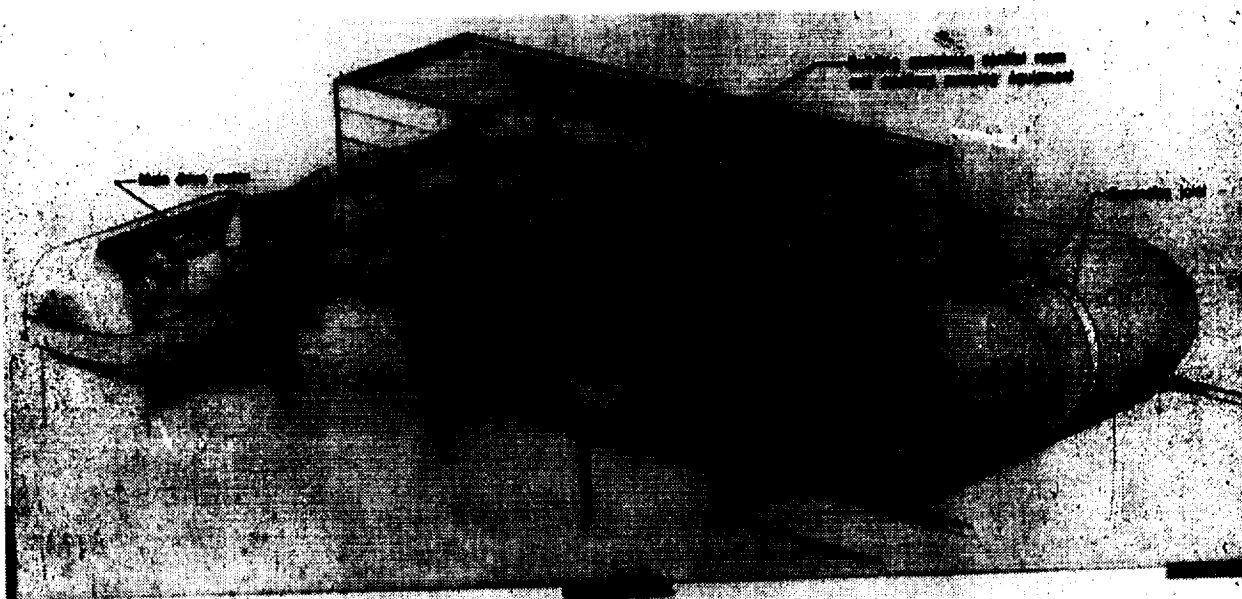


Figure 1. Langley's 8-ft Transonic Pressure Tunnel.

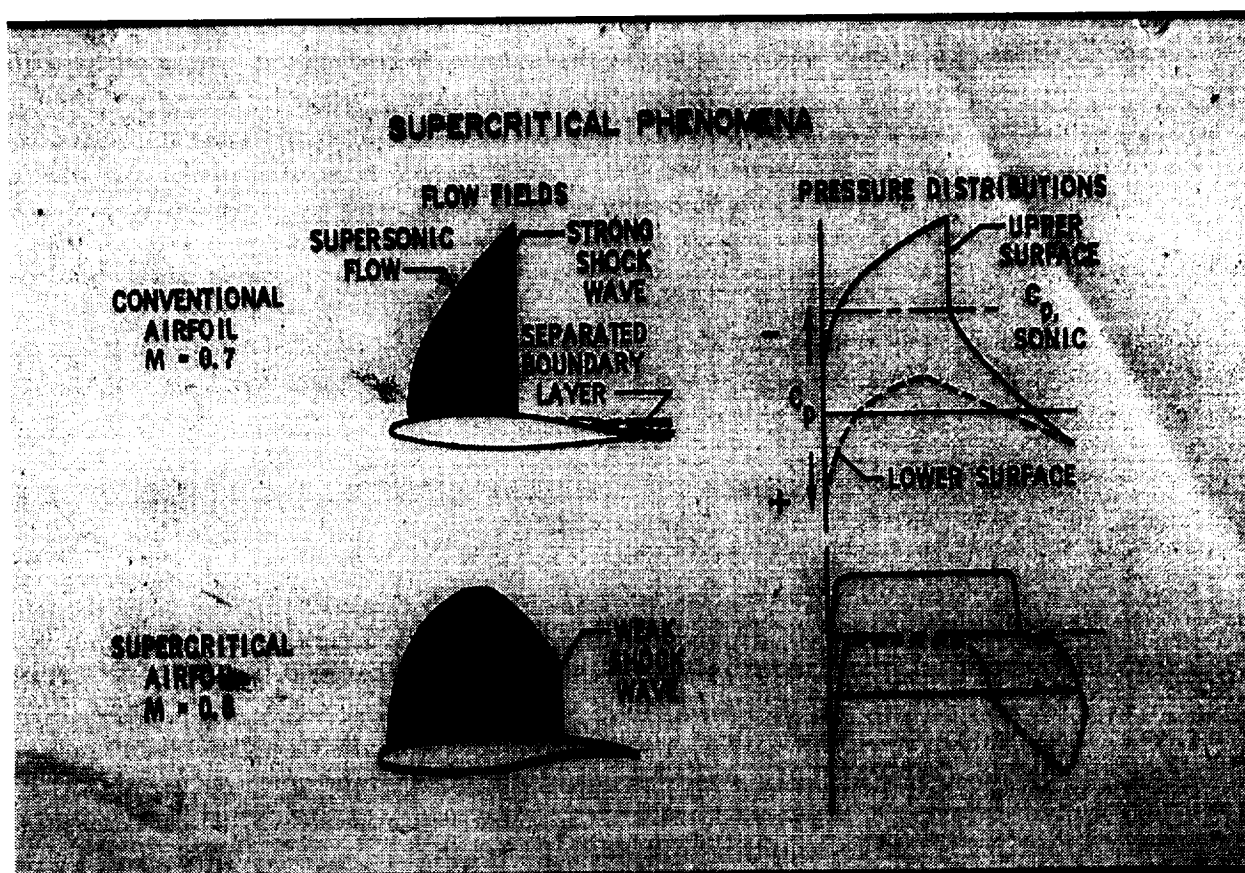


Figure 2. Supercritical wing flow field.

It was the first time a large, two-dimensional airfoil designed to take advantage of the shock waves had been tested. There was an interesting thing here that nobody picked up on for years. We used this schematic (fig. 2) to explain supercritical flow and if you'll note, the conventional airfoil has a large area of supersonic flow terminating in a shock wave which results in separated flow and very high drag. I show this here only to make a point; while we thought we were doing everything right in the tunnel, the real supercritical airflow shown down here was what we were after. In fact, this airfoil was going to generate so much lift that it was mounted upside down in the tunnel to prevent the test section from lifting off its mounts. This test section (fig. 3) weighs nearly 30 tons.

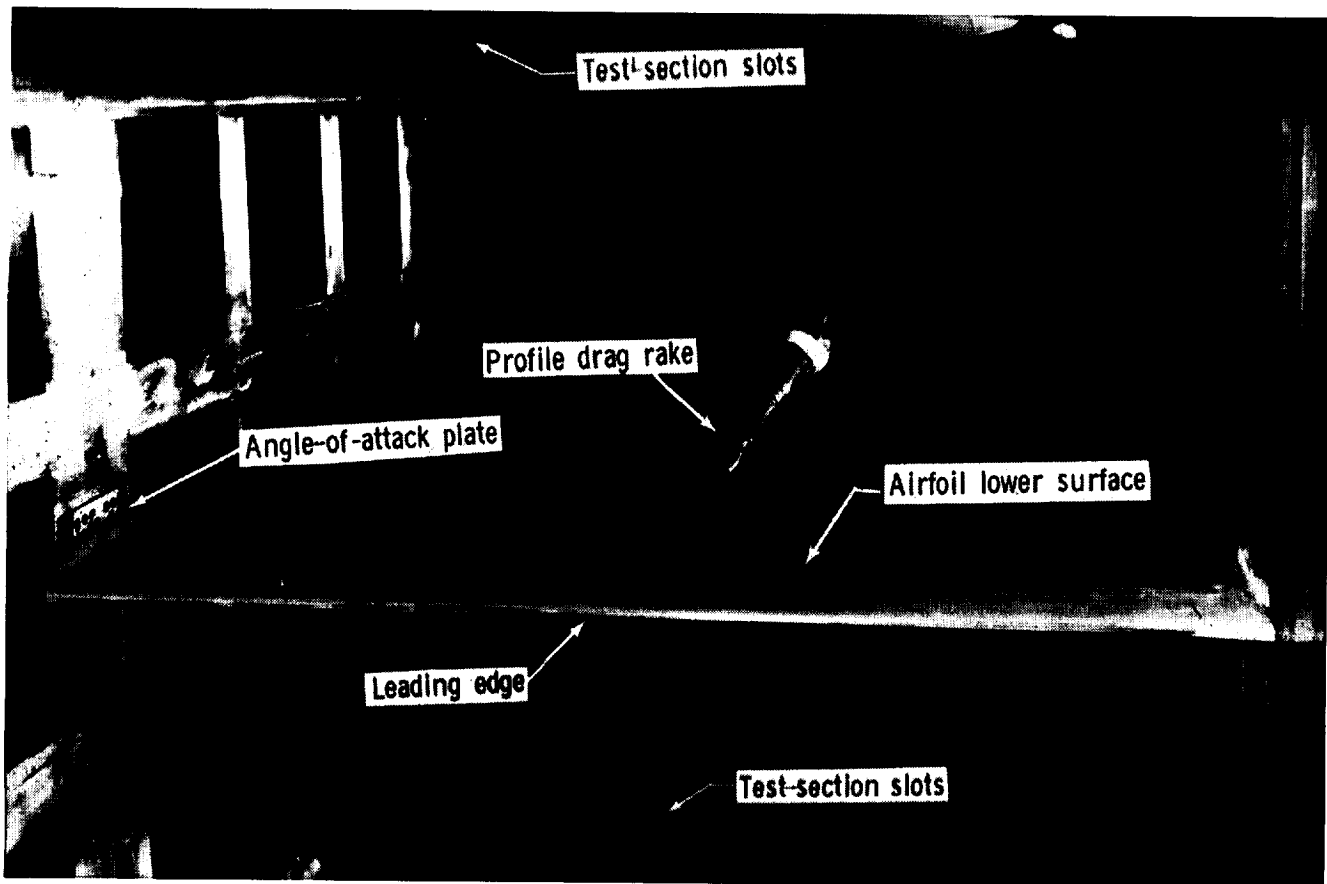


Figure 3. 2-D supercritical wing model.

The other thing that was unique about this supercritical airfoil was that when we tested beyond the design Mach number, the shock wave would “pop” off its design location and the whole building would rumble because of the separated flow. While many changes could be made to this large, heavy model in the tunnel using the previously mentioned body putty technique, some major design changes required the model to go back to the machine shop six miles away. On one such occasion the model was being returned from the shop for the next series of tests - I need to tell you that when Dick Whitcomb was on to something he was really focused, it was like—here we go, don't bring any side shows. Now the road from the shop to the tunnel ran through the Langley Air Force Base NCO housing area which had two 90°-turns. This road represented a significant delay to the research because the wing, this large, two-dimensional wing, neglected to follow the truck through the 90°-turn and ended up skidding down the main street in the NCO

housing area. Obviously this didn't set very well with Dick. So people kind of stayed away from him for a few days while he cooled down and we got the model repaired.

Having overcome this setback, the research continued and another first occurred. Because of the airfoil design and the need for a critical positioning of the shock wave, understanding the boundary layer was very important. Dick may have more to say on this subject, but I did want to show here the sophisticated techniques that we used to control boundary-layer transition. There were two ways of doing this. One was to feed carborundum grains to a fly and make him walk along here to deposit them; the second one was to find one of the technicians that could blow real well and put it on there with a piece of paper.

The research continued as the airfoil became refined. It transitioned from the 2-dimensional slotted airfoil to a 2-dimensional unslotted airfoil with a thick trailing edge. It seemed that thickening the trailing edge improved the flow characteristics. So much emphasis was placed on squeezing the last bit of performance out of this area with the final shape looking like this latter one in figure 4. You may wonder, "How did this shape get to be this way, why this?" Well, supercritical flows and weather have something in common. Shown by figure 5 here, this is a snow cornice theory published in the literature and thus the reason for the cusp and the trailing edge for the supercritical wing. That was the reason that the trailing edge on the F-8 ended up this way (fig. 6).

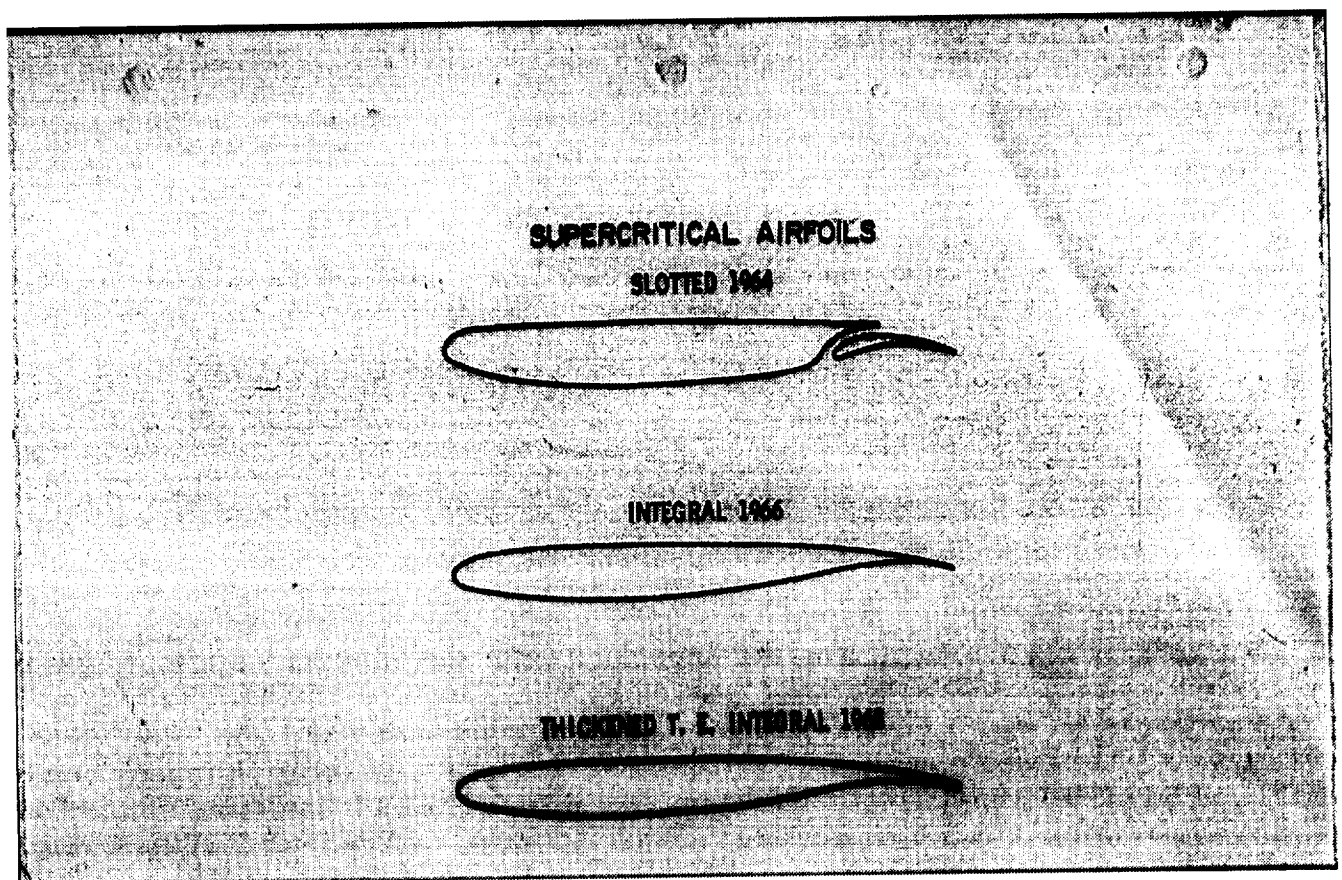


Figure 4. Supercritical wing design optimization.

- HARRIS - REF (3)

OSMAN MESKENTAN
Research Building
American University
Washington, D. C.
April, 1966

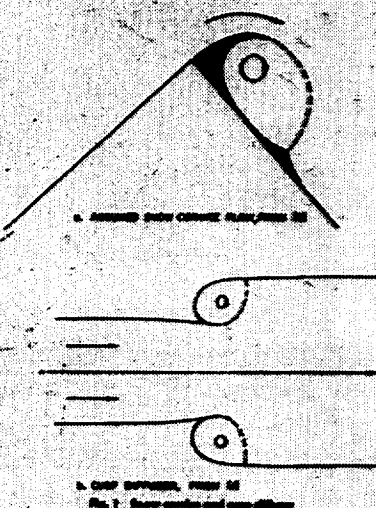
Remarks on Snow Cornice Theory and Related Experiments With Sink Flows

A review is made of Knight's theory on snow cornice formation and of the published, unsuccessful attempts at experimental verification. Arguments are presented which render the theory an entirely representative of real fluid flow. The flow over a down-sloping step in a channel, with either of two types of sink located immediately downstream of the step, was investigated experimentally. A vortex and associated smooth expansion of the exterior flow behind the step were established for relatively high sink rates. A model of the step-sink flow is suggested and general conditions are outlined.

Introduction

One exploratory study was prompted by a theory proposed by Knight in a series of publications on what has become known as the snow cornice or step effect and by subsequent attempts made by him and others at experimental verification of the theory.

Previous investigators (1) and those of Wilcox (2), Knight suggested that the snow cornice constitutes a vortex on the lee side of a mountain ridge represents a natural phenomenon which causes the wind on the windward side of the ridge to expand smoothly over the ridge onto the lee side under the influence of a vortex situated in the cavity behind the upwind edge of the cornice. Fig. 1(a) has been freely copied from (2) and represents schematically the type of flow being considered. Knight proposed a potential flow model for the step flow. It is a flow over a step in a channel, with either of two types of sink located immediately downstream of the step. The flow is assumed to be inviscid and incompressible. The potential function for the flow is assumed to be the same as the potential for the flow over a step in a channel, with either of two types of sink located immediately downstream of the step. The potential function for the flow is assumed to be the same as the potential for the flow over a step in a channel, with either of two types of sink located immediately downstream of the step.



Manuscript received at ASME Headquarters, July 20, 1965. Paper No. 65-40000.

Q = sink strength	H = step height	q = required q , for smooth expansion
r = vortex strength	I = step inclination to step	U = uniform approach velocity for model geometry
$s = \pm \sqrt{1 - \frac{r^2}{Q^2}}$	i = sink location relative to H	U_{∞} = sink strength for model geometry
x, y = rectangular coordinates in x, y plane	Ap = atmospheric pressure minus local total pressure	U_{∞} = sink strength for model geometry
x, y = vortex location in x, y plane	Q = volumetric sink flow rate	U_{∞} = sink strength for model geometry
x, y = stagnation point in x, y plane	U = center line duct velocity ahead of test section	U_{∞} = sink strength for model geometry
x, y = sink location in x, y plane	$U_{\infty} = U$, for any sink flow, duct for duct flow	U_{∞} = sink strength for model geometry
x, y = rectangular coordinates in x, y plane	$U_{\infty} = U$, for any sink flow, duct for duct flow	U_{∞} = sink strength for model geometry
x, y = vortex location in x, y plane	$U_{\infty} = U$, for any sink flow, duct for duct flow	U_{∞} = sink strength for model geometry
x, y = sink location in x, y plane	$U_{\infty} = U$, for any sink flow, duct for duct flow	U_{∞} = sink strength for model geometry
x, y = duct width = duct height	$U_{\infty} = U$, for any sink flow, duct for duct flow	U_{∞} = sink strength for model geometry

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Figure 5. Snow cornice theory.

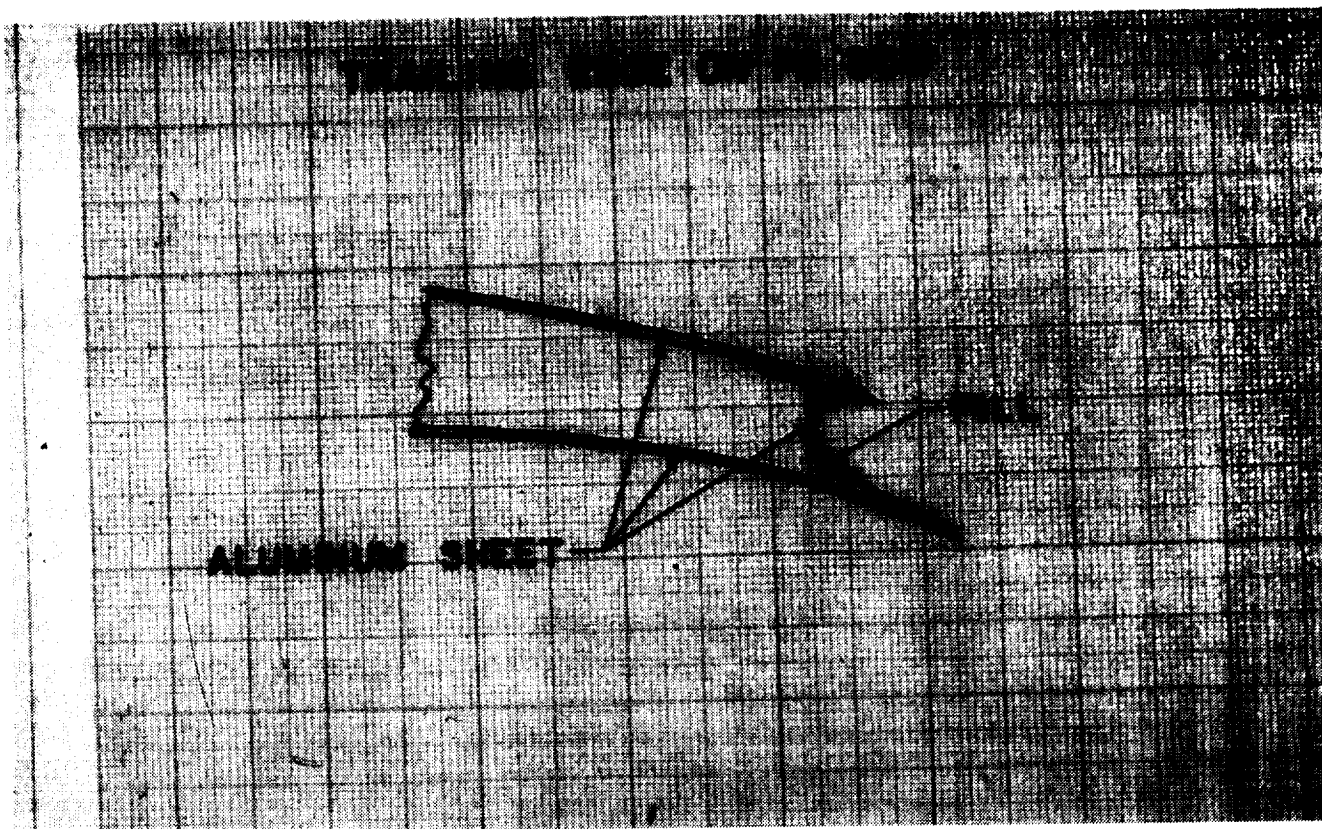


Figure 6. Trailing edge on F-8 SCW.

Remember that I started out by saying that good theoretical predictive tools were essentially nonexistent during this time period. Somewhere along the way, and I don't remember exactly when, the folks at Lockheed came up with a 2-dimensional attached flow code that could compute pressure distributions. Up until this time everything was done on a piece of paper. This code was eventually modified for use as a design code that allowed one to specify the desired pressure distribution and compute the airfoil geometry. However there was still a problem, we still needed to know what the boundary layer was to get the viscous effects on it.

What's the point of mentioning this? The point is that the experimental research in supercritical aerodynamics spawned a renewed interest in computational fluid dynamics (CFD) that led to the development of very sophisticated transonic computational design and analysis methods.

In fact, here's an example of an early design approach, this being the solution to potential tip flow problems on the F-8 Supercritical Wing. Figure 7 is a picture of an original hand-sketches drawing, so this was CFD without a computer.

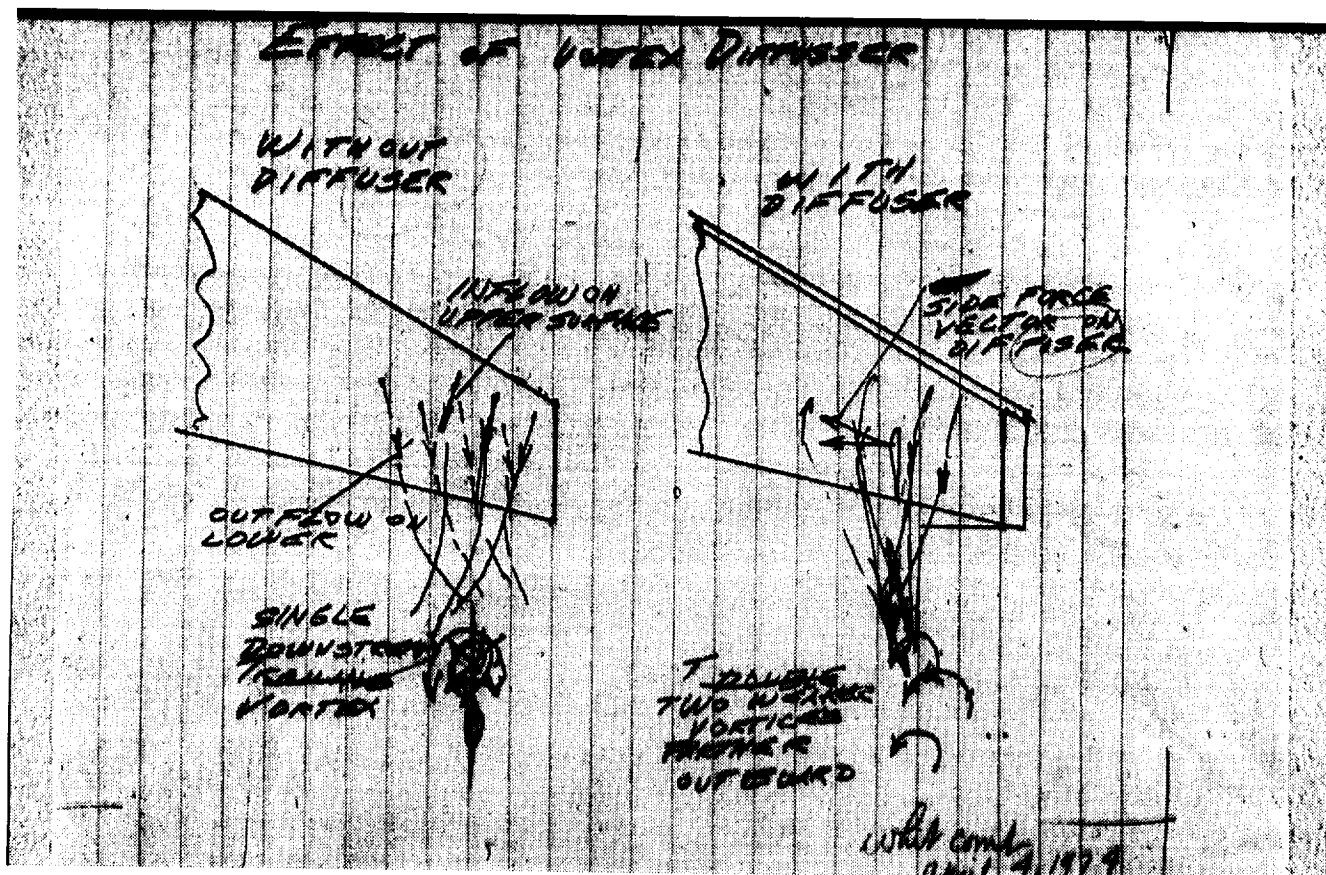


Figure 7. Effect of vortex diffuser.

Having completed the airfoil development, or at least carrying it far enough to prove its feasibility and being well aware of all the problems associated with practical transonic flight, it was decided that an actual flight research program was in order to dispel any myths about this new airfoil. Believe me there were myths; like anything new, people were skeptical. Many believed that any benefits derived from this airfoil would be offset by trim drag, flutter, buffet, and the practicalities of fabrication. At the time of the supercritical wing research, Larry Loftin was director of aeronautics at the Langley Research Center, and he gave the flight research idea a thumbs up. Larry was such a key part of this activity and such an admirable speaker we had hoped to get his views on airplane design. Unfortunately, Larry is unable to be with us today. The decision was made to conduct the flight research at Dryden.

The F-8 Supercritical Wing flight project was thus born. The Langley Research Center Wind Tunnel testing continued to define the flight configuration. More firsts were in store. We had long known that our atmospheric open-circuit wind tunnels contained moisture and that its effects were not well understood. When we went from atmospheric wind tunnels, where outside air was used to replenish inside air without conditioning it, to the pressurized closed-circuit tunnels where we could control temperature, pressure, and other parameters, we more or less assumed that the moisture content was low enough so as not to be a problem. However, we began to see differences in test data, at near sonic velocities, that led us to suspect that this might not be the case.

These suspicions led to yet another spinoff of supercritical aerodynamic research. This was an increased insight into the effects of moisture on the location of shock waves or shock condensation effects. Our research into shock condensation phenomenon was carried out in a very sophisticated manner. We would throw a cup of water in the tunnel, run it, then throw a bucket of water in the tunnel and run it, then throw more buckets of water in the tunnel and run it. We did this until we were able to define the critical temperature and humidity levels at which shock condensation effects appeared in the data.

Another spinoff from the F-8 Supercritical Wing research was that of wind tunnel blockage at near sonic velocities. The development of a slotted transonic wind tunnel was intended to somewhat alleviate the effects of blockage. However, concern for the potential disastrous effects that blockage could have on wind tunnel drag results at the approximately Mach 1 design cruise conditions led to another research effort focused on understanding this blockage and its consequences. A series of equivalent bodies of revolution; i.e., a body of revolution having the same longitudinal area distribution as the F-8 Supercritical Wing airplane, were constructed and tested in the Langley 8-ft and 16-ft wind tunnels and the Ames 11-ft wind tunnel. It was this research that provided an understanding of blockage effects and allowed for its consideration in assuring the accuracy of the F-8 Supercritical Wing drag predictions.

One other area I would like to touch on has to do with testing philosophies. Early on, it was believed that the design conditions, that is Mach 1 cruise, dictated that all testing be done with the wind tunnel model wing fabricated to the 1-g design load shape. Generally wind tunnel models are built to the design jig shape which is an unloaded condition, and then the wind tunnel tends to load it up to some extent and you try to make corrections for the difference between that and the airplane. In the case of the F-8 we believed that the shock location was so critical to the boundary-layer stability that the wing on the wind tunnel model had to be exactly the same as the wing on the airplanes. Therefore, the airplane design specification required the full-scale wing be designed to match the wind tunnel shape at that 1-g loaded condition. So, another first was achieved; aeroelastic tailoring. We generally think of aeroelastic tailoring as the result of control using composite materials overlaid in a strategic manner to control the shape of a wing as it undergoes aerodynamic loading. In the case of the F-8 it was the reverse, i.e., we designed the airplane to be like the wind tunnel model.

Figure 8 is a comparison of the wing box deflection versus the semi span for the predicted ability of deflection. The difference between these two is the jig shape.

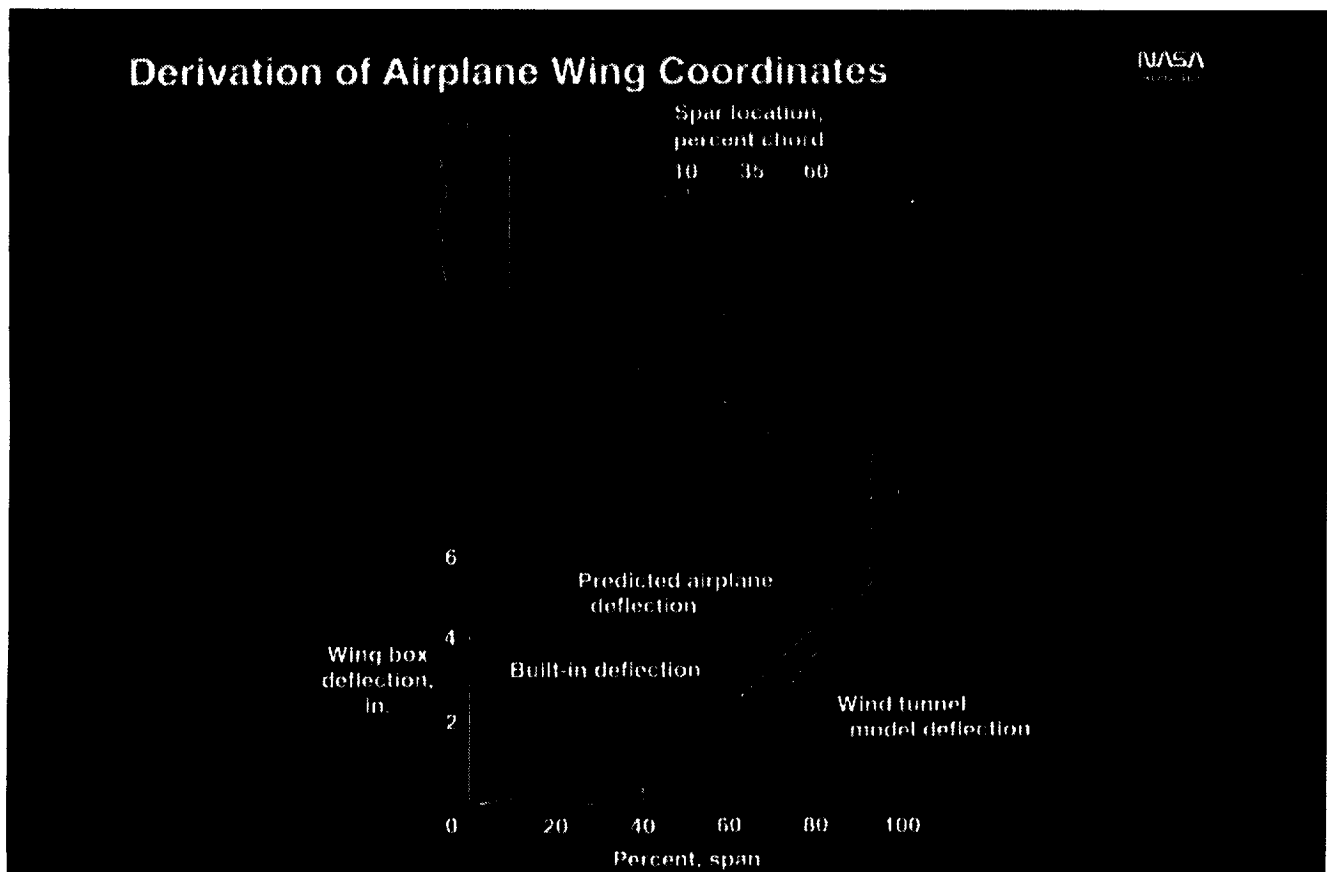


Figure 8. F-8 SCW wing geometry.

Finally, in keeping with Dryden's low-cost and simple approach to flight testing, the F-8, so I'm told, represented the first and last attempt to conduct a load calibration using lead shot. The lead shot was purchased from shotgun reloading stores, used to load the wing, and then sold back to the reloading store. As shot was added to increase the wing loading, the actual wing mass was increased causing the wing to resonate. This approach, while low cost, did require very careful placement of the load to insure that the wing did not fail during the loads calibration. This actually saved money, but did create other problems. Test results are shown in Figure 9 compared with predictions.

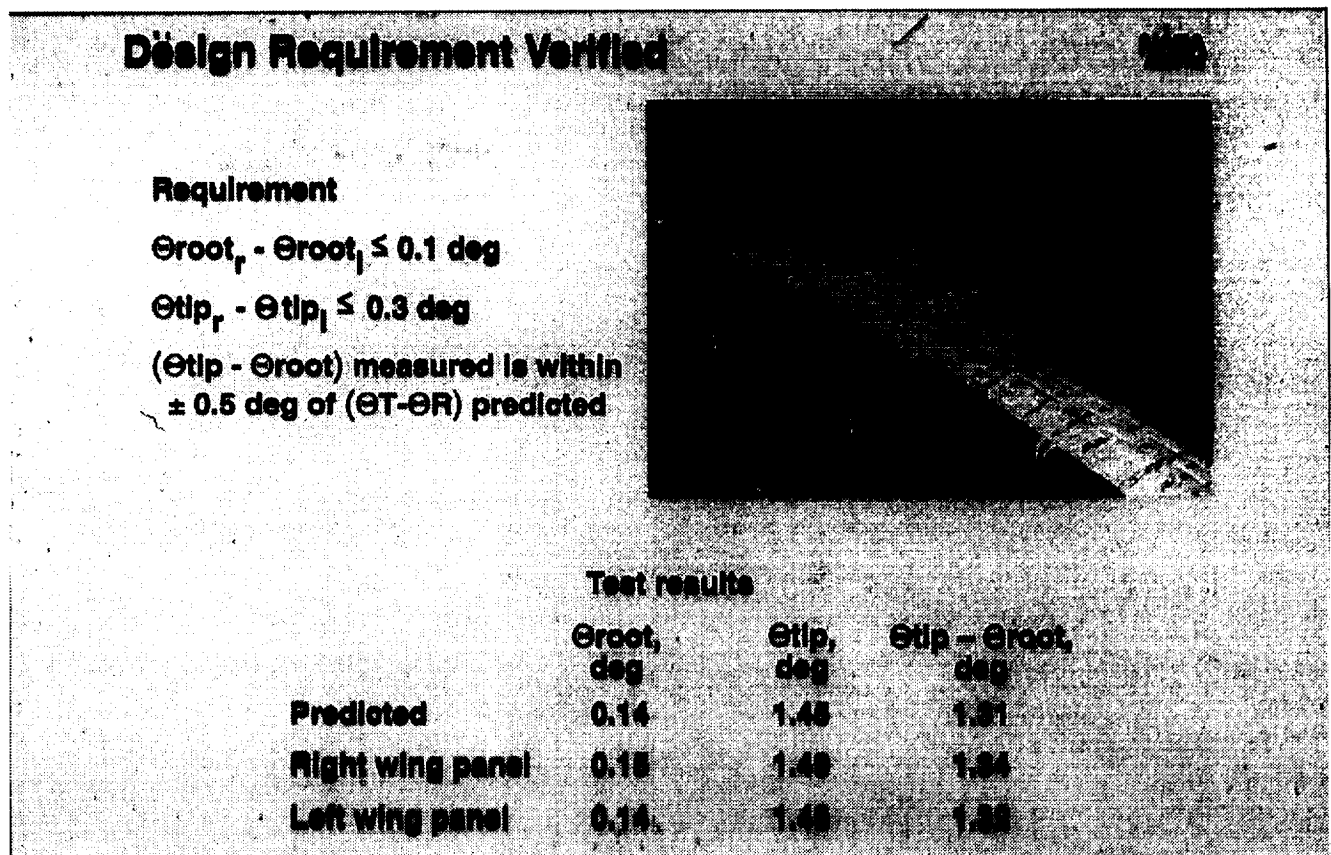


Figure 9. Design requirement verified.

And now, as Paul Harvey says, "you know the rest of the story." Well not quite. During the F-8 Program, it was discovered that while the airplane generally performed as anticipated and did cruise at approximately Mach 0.97, differences still existed. The discovery was that the airplane actually had some laminar flow on the wing, resulting in a thinner boundary layer and therefore, an increase in the effective camber of the wing. This was not predicted. "And now you know the rest of the story."

My point is that while we continue to develop new methods, new techniques, and continue to learn more, we continue to find out that there are still many unknowns. Only through actual flight research do we discover these phenomena. The other point I want to make here is that for those who believe that flight projects are only there to support ground-based research, the F-8 Supercritical Wing stands as an example of where flight activity provided a focus to enhance our overall knowledge of transonic flows.

At this point, it is my pleasure to introduce to you one of the true icons in the world of aeronautical research. This is the man I have had the privilege and the pleasure of working for and with, I've known him for over 30 years. He was my first boss, and my first real professor in transonic aerodynamics.

Richard Travis Whitcomb was born in Evanston, Illinois; he attended Worcester Polytechnic Institute graduating with high distinction in 1943 with a Bachelor of Science degree in mechanical engineering. He went to work at Langley and was associated with the Transonic Aerodynamics Branch at the Langley Research Center from 1943 to 1980, when he retired. He was appointed head of the branch in 1958 and

throughout his career supervised the development of means for improving aerodynamic performance of aircraft. Dick always had an eye toward practicality, improvements to aircraft at transonic speeds, and the practical application to specific airplanes. He's the author of over 30 technical papers on transonic aerodynamics and he's an instructor in the graduate program at Langley. Since his retirement from NASA he has continued to be active, although now he tells me he's in a voluntary role to teach high school kids how to build 30-ft flying paper airplanes.

In 1952, Whitcomb discovered and experimentally verified a revolutionary aircraft design concept called the area rule. This is a method of designing aircraft to reduce drag and increase speed without additional power. It has been incorporated into almost every American supersonic aircraft. He was also the inventor of the supercritical wing that we're talking about today. In addition, he invented and developed the application of winglets to transport airplanes and other vehicles to increase their lift-to-drag ratio. He's an internationally known aerodynamicist, he's received awards too numerous to cover in totality; he was awarded the Collier Trophy in 1954 for the year's greatest achievement in aviation in America, the Exceptional Service Medal of the Air Force in 1955, the first Distinguished Service Medal to be presented by NACA in 1956; he received the NASA Scientific Achievement Medal in 1959, in 1974 he received a cash award of \$25,000 for the invention of the supercritical wing, he was selected to receive the Aircraft Design Award from the AIAA, and on and on.

Chuck Yeager may have broken the sonic barrier, but Dr. Richard T. Whitcomb made routine transonic or supersonic flight a reality. Please welcome Dr. Richard Whitcomb.

THE STATE OF TECHNOLOGY BEFORE THE F-8 SUPERCRITICAL WING

Richard T. Whitcomb

I should explain what supercritical means. Critical Mach number is the speed at which local supersonic flow develops on the wing or any other part of the configuration, and super obviously means "beyond" just like supersonic means beyond the speed of sound. The first airfoils designed to operate efficiently at supercritical Mach numbers were the Percy Airfoils, which were used on the second generation of transports. The Percy Airfoil, which delayed the drag-rise Mach number about .02 or .03, had a limited region of supercritical flow on the upper surface, about 5 to 10 percent of the chord near the leading edge. Percy didn't take the next step which was to design an airfoil with a large region of supercritical flow above the airfoil. With such an airfoil, one should achieve large delays in the drag rise Mach number. A schematic of the airfoil resulting from our work is shown in figure 1.



The well-known flow problem for conventional airfoils at high subsonic speeds is illustrated at the top of figure 1. A local region of supersonic or supercritical flow develops above the upper surface of a lifting airfoil which terminates in a strong shock wave. The wave itself causes some increase in drag, but usually the principal effect is separation of the boundary layer with a significant increase in drag, stability problems, and buffet. For the NASA supercritical airfoil shown at the bottom of figure 1, the curvature of the middle region of the upper surface is substantially reduced with a resulting decrease in the strength and

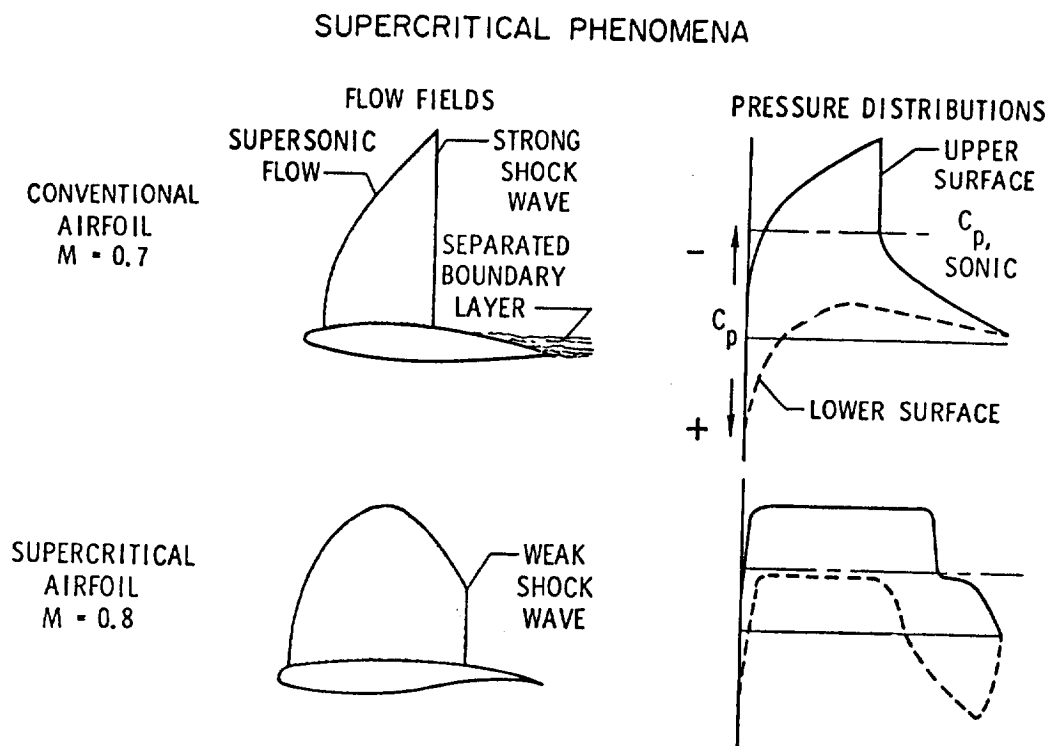


Figure 1. The supercritical phenomena.

extent of the shock wave. The drag associated with the wave is reduced and, more importantly, the onset of separation is substantially delayed. The lift lost by reducing the curvature of the upper surface is regained by substantial camber of the rear portion of the airfoil.

The airfoil also incorporated other features which were important to the total effectiveness of the new shape. The middle region of the lower surface was designed to maintain subcritical flow for all operating conditions of the airfoil, because the pressure rise associated with a shock wave superimposed on the pressure rise caused by the cusp would cause separation of the lower surface boundary layer. To minimize the surface curvatures and thus the induced velocities on the middle regions of the upper and lower surfaces, the leading edge was made substantially larger than for the previous airfoils. It is approximately 2.5 times that for a 6-series airfoil of the same thickness ratio. The pressure distribution on the aft portion of the lower surface was designed by the Stratford criteria to obtain the largest increase in lift by the cusp without incurring boundary-layer separation in the cusp. This involves a rapid initial increase in pressure followed by a more gradual increase. Finally, at the trailing edge the slope of the lower surface was made approximately equal to that of the upper surface to reduce to a minimum the required pressure recovery at the upper surface trailing edge.

The development leading to the shape shown in figure 1 is shown in figure 2. For years people had been trying to control the boundary-layer separation under the shock wave. The devices used, blowing and sucking, for example were far too complicated. If you just put a slot in the airfoil as shown in figure 2, then the flow through the slot stabilized the boundary just like for a slotted flap at low speed. The action of this slot is essentially the same as for low speeds but the slot was designed with much more care because the flow through it is near sonic and it has to be exactly right. The industry thought the slotted airfoil was too complicated, so we developed the integral airfoil shown.

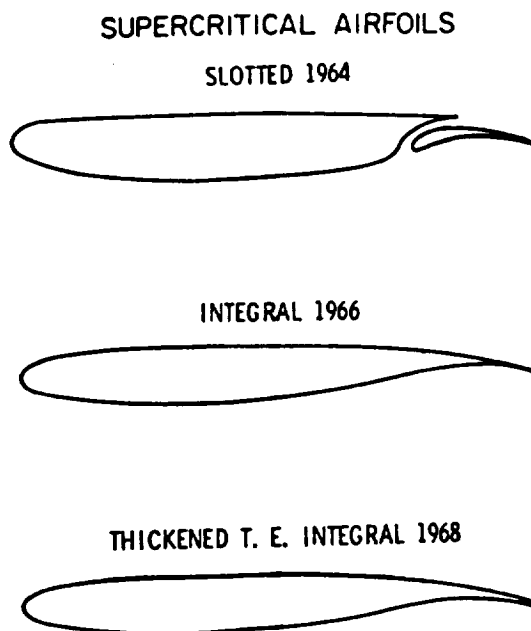


Figure 2. Supercritical airfoils.

Another thing that the industry didn't like was the thin trailing edge, so we thickened it. Here we got into a disagreement with almost every aerodynamicist in the whole industry, they said, "You can't do that,

it will cost you drag!" But if you kept the thickness small enough, there was no drag penalty. Any airfoil that has ever flown had separation near the trailing edge. What we did was move the separation around to the base.

Figure 3 presents variations of drag with Mach number for an airfoil similar to that used on the out-board part of the F-8 wing for a normal force (lift) coefficient of 0.7. This value is substantially higher than the lift coefficient at which the F-8 would fly. The sweep of a wing reduces the lift produced by an airfoil by the cosine of the sweep angle squared. Thus, the airfoil must be optimized for a higher coefficient. For comparison, the variation for a NACA 64 series with the same thickness ratio and normal force coefficient is also shown.

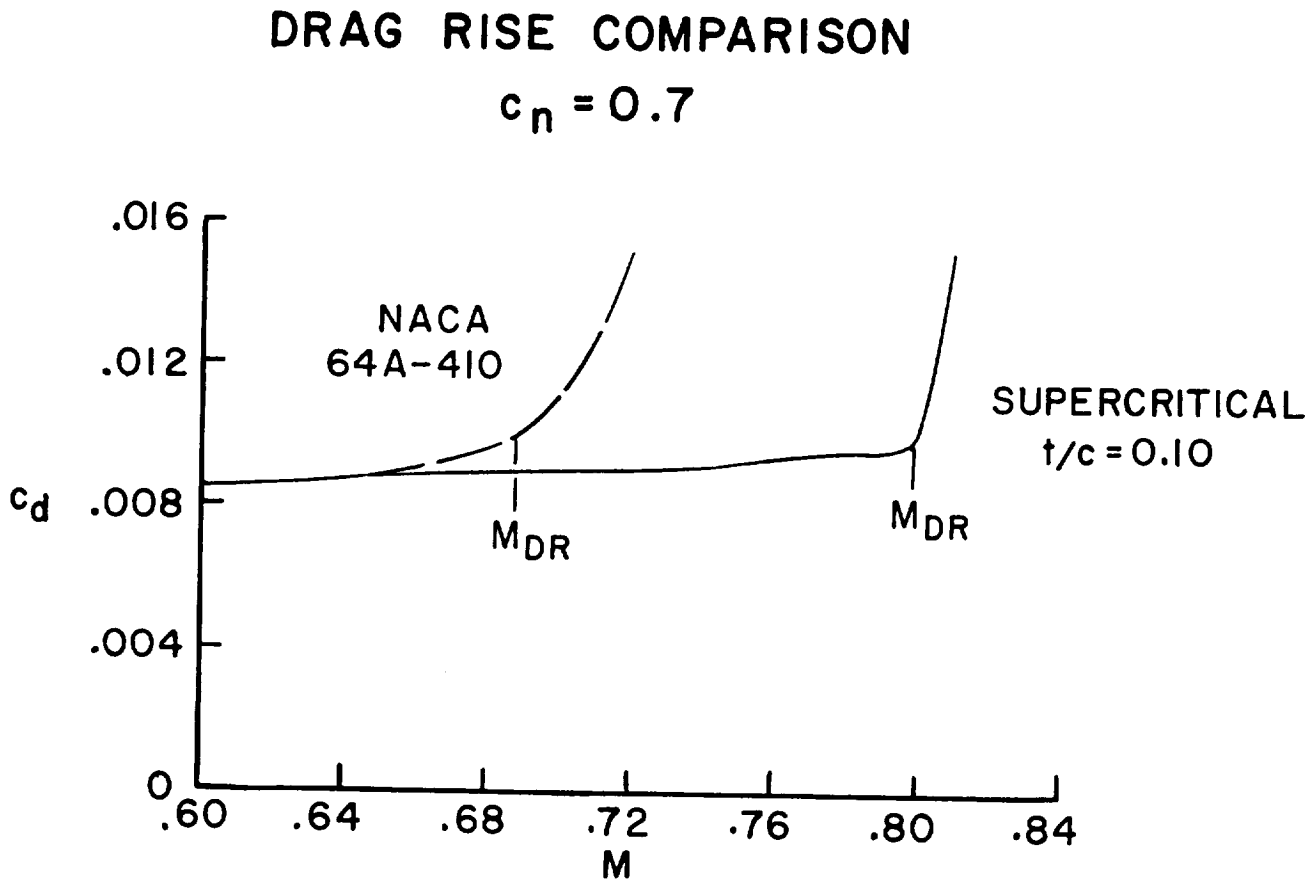


Figure 3. Drag rise comparison, $c_n = 0.7$.

The drag rise Mach number is about 0.11 higher for the supercritical airfoil. This comparison was criticized by people in industry since we didn't compare the new airfoil with the most recent Percy airfoil already mentioned. The problem is that Percy never published any airfoil data which could be used. He presented coordinates, selected pressure distribution, and some drag data, but not enough to make a valid drag rise comparison. Using drag rise data for complete wings with the Percy airfoil and the 64 series airfoil, we estimated that the drag rise values for the former were about .02 to .03 higher than for the latter. A comparison of the variation of the drag rise Mach number with normal force coefficient, presented in figure 4, shows that not only is the Mach number for drag rise increased but also the normal force coefficient for stall improved. Thus, the new airfoil should improve the maneuver characteristics of fighter-type

airplanes at high subsonic speeds. On the basis of results such as these shown, the new supercritical wing panels for the General Dynamics F-111 were flight tested here at Dryden. They substantially improved the maneuver characteristics.

ONSET OF DRAG RISE

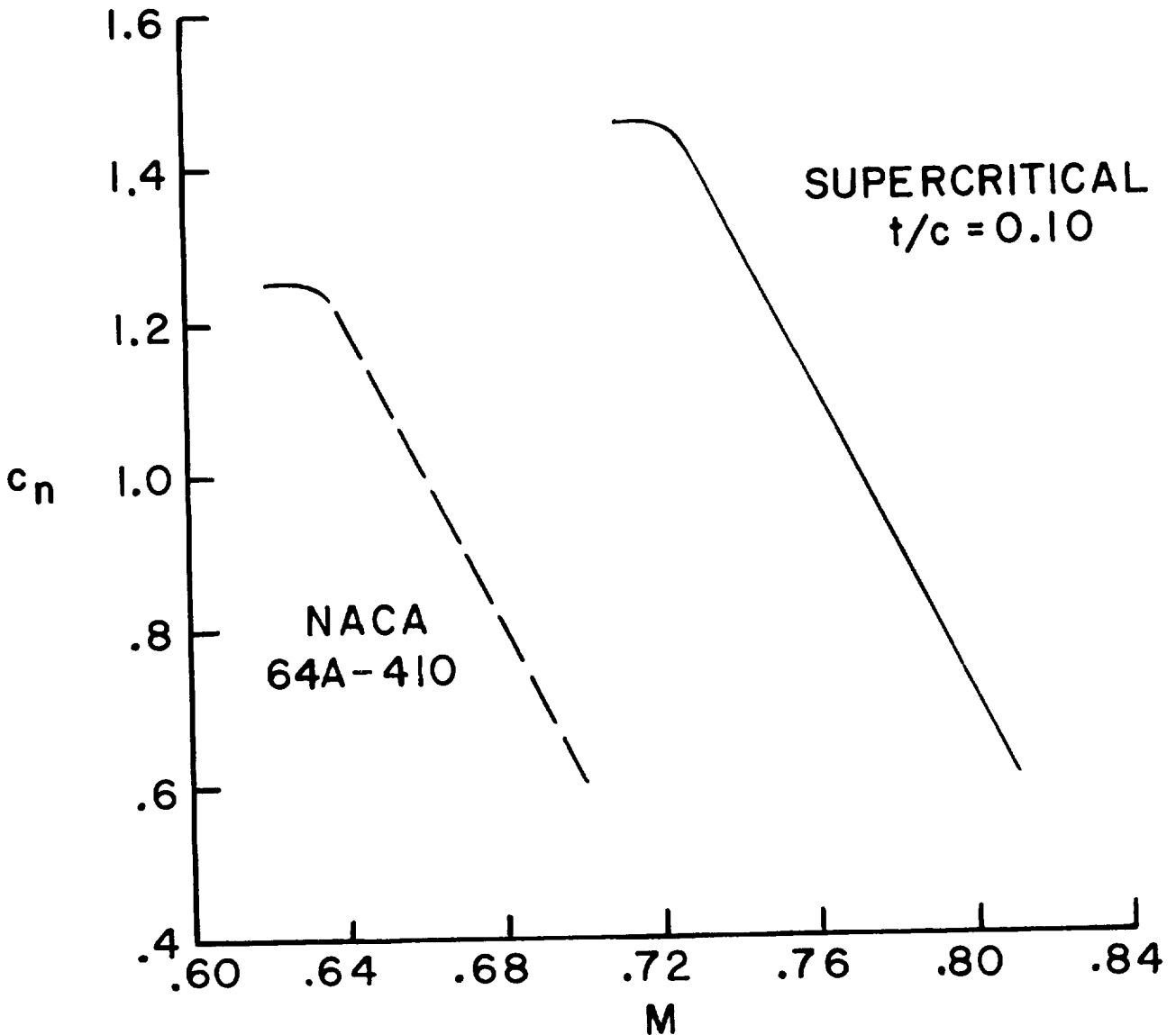


Figure 4. The onset of drag rise.

Ted noted that we had to develop the new airfoil experimentally because no theory for supercritical flow was available. Larry Loftin said, "We've got to have a theory!" Clint Brown, who used to work at Langley, recommended Garabedian at the Applied Math Department at NYU, since nonlinear mathematics would be required and Garabedian had written a book on the subject. We gave Garabedian a large grant to support a group to work on the problem. He proposed a method for computing supercritical flow which he

presented to us. I was supposed to manage the grant, but I was no mathematician. Loftin had Ed Garrick, one of Langley's best mathematicians, look at the proposal. Garrick, who had grown up with linear theory, said, "It's brilliant but I don't understand a word of it." Now there are many nonlinear theories for supercritical flow.

As Ted pointed out, Yoshahara developed a theory but it wouldn't converge. He spent all night on the fastest Langley computer and it hadn't even started to converge.

Any method for computing the real aerodynamics for supercritical airfoils must have the effect of the boundary layer in the computations. A schematic of the boundary layer on the aft part of a supercritical airfoil is shown in figure 5. Because of steep pressure gradient on the aft part of the upper surface, the boundary layer in this region greatly thickens as shown. Also, the steep gradient on the mid part of the lower surface also thickens the boundary layer in the cusp of this surface. Both of these effects greatly reduce the effective camber for the airfoil.

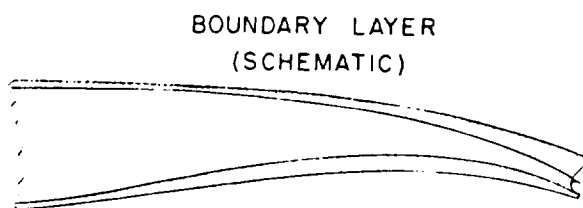


Figure 5. Influence of boundary-layer displacement on effective camber of supercritical airfoil.

As Ted mentioned, the other thing Larry said was, "We're going to have a flight demonstration. This thing is so different from anything that we've ever done before that nobody's going to touch it with a ten foot pole without somebody going out and flying it." So he said, "We'll fly it!" We decided the Navy F-8 would be the best test bed. Loftin talked with a man high up in the Navy Bureau of Aeronautics, who provided us with an airplane. We finally got some money from Washington headquarters and the wing was built by North American in California.

Let's talk about the configuration. The F-8 with the new supercritical wing on it is shown in figure 6. I decided somewhere along the way to try to get a cruise Mach number as close to $M = 1.0$ as possible. I wanted to have a "sonic" transport. I had worked on a supersonic transport configuration for about four years and had decided that supersonic transports were totally impractical from the standpoint of operating cost. Ask the British and French about that. Every year they fly the Concord they lose their shirts and yet it's a matter of national prestige that they fly those airplanes. They built about ten of them but only use seven because so few people wanted to pay the ticket price required. It's very high! The high cost results primarily from the high drag at supersonic speeds which greatly increases fuel consumption.

To get the drag rise for the wing up to near $M = 1.0$, we increased the sweep to 42° . In addition, we wanted ultimately to design a total airplane on the basis of the area rule. To obtain a reasonable indented fuselage, the increase in cross-section area for the wing should be relatively gradual. We achieved this by extending the leading edge of the inboard section of the wing forward as shown in figure 6.

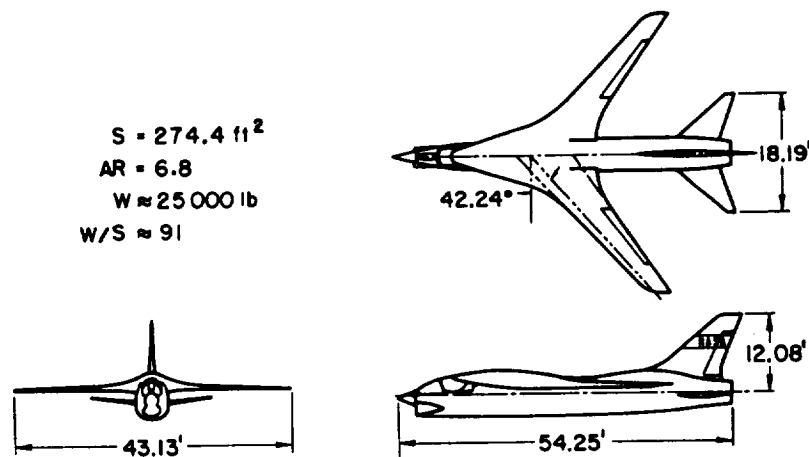


Figure 6. Three-view of F-8 Supercritical Wing airplane.

The shapes of the airfoil sections are shown in figure 7. Most of the airfoils for the outboard region are the same as we had developed two dimensionally. However, the root section did not look like those airfoils, since there was a strong three-dimensional effect near the root. It still has a lot of aft camber in this region, but it doesn't have that severe curvature near the trailing edge of the upper surface. As for this region of previous transports, it has very little curvature in this region. The spanwise variations of section thickness ratios and incidence are shown in figure 8.

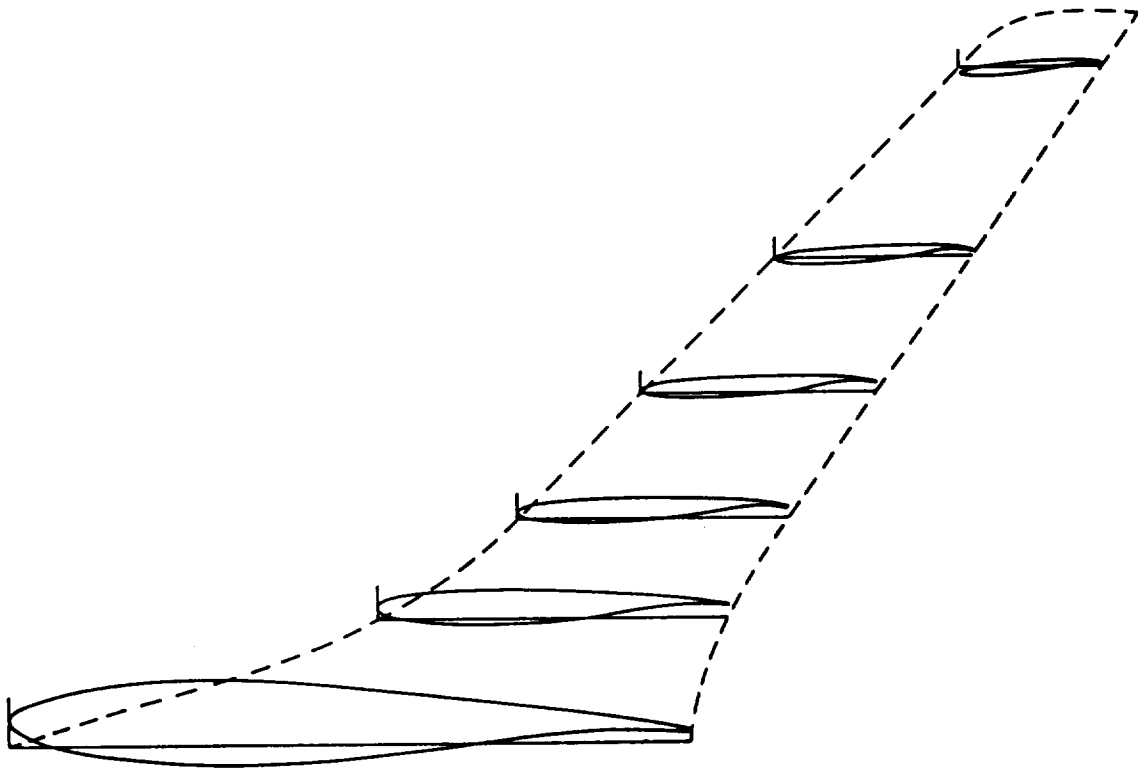


Figure 7. Supercritical wing on the F-8 research airplane.

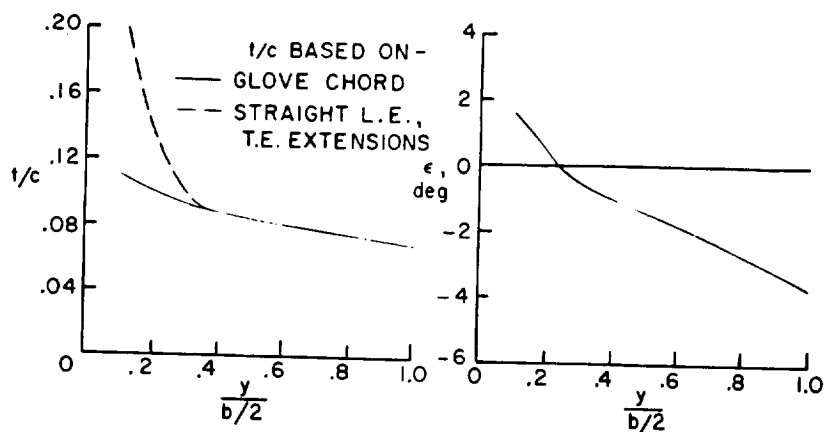


Figure 8. Spanwise variation of thickness and twist.

The available subcritical theory indicated that because of the high sweep and Mach number, the wing should have a large amount of twist. With supercritical flow present, it should have even more. We arbitrarily moved 2° for this effect. Now let's look at the thickness ratios, t over c . As you can see, there is a large spanwise variation in thickness ratio, again this is similar to previous transport airplanes.

Now let's discuss one of the problems we encountered. We had increased the sweep and aspect ratio so that we were guaranteed to get pitch up. I made a presentation at Langley on some of our data. Jack Reeder, the chief test pilot at Langley, who was in the audience, said, "You can't have that." So I said, "We'll fix it." We added a little surface which extended below the leading edge of the wing as shown in figure 9. Oil flow studies with and without this addition are shown in figure 10. You can see that on the original wing without the addition, the boundary-layer flow zipped spanwise across the wing indicating that the boundary layer was separated. When we put the addition on, an opposing vortex on the upper surface stopped the spanwise flow on the wing. It's an aerodynamic barrier, not a physical one, like a fence. The effect of the addition on pitch up is shown in figure 9.

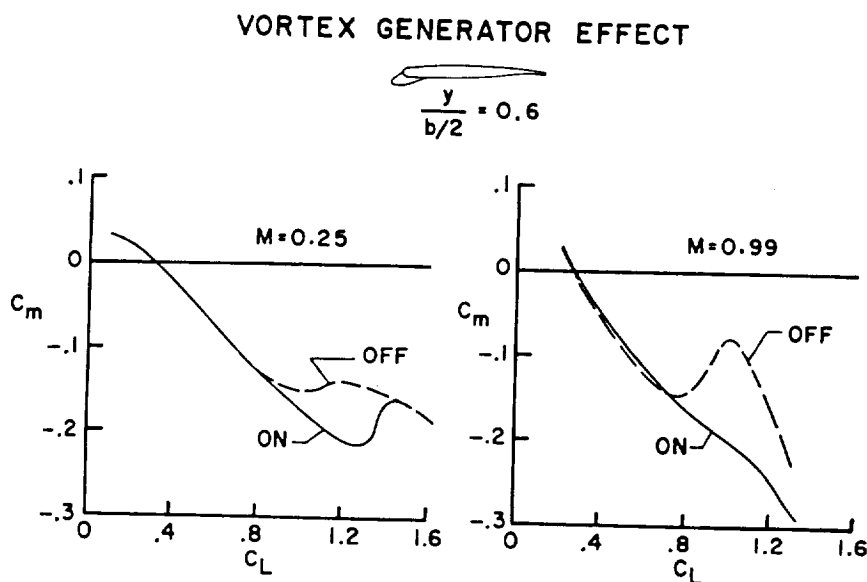


Figure 9. Vortex generator effect.

OIL FLOW

VORTEX GENERATOR EFFECT

$M=0.95; C_L \approx 0.93$

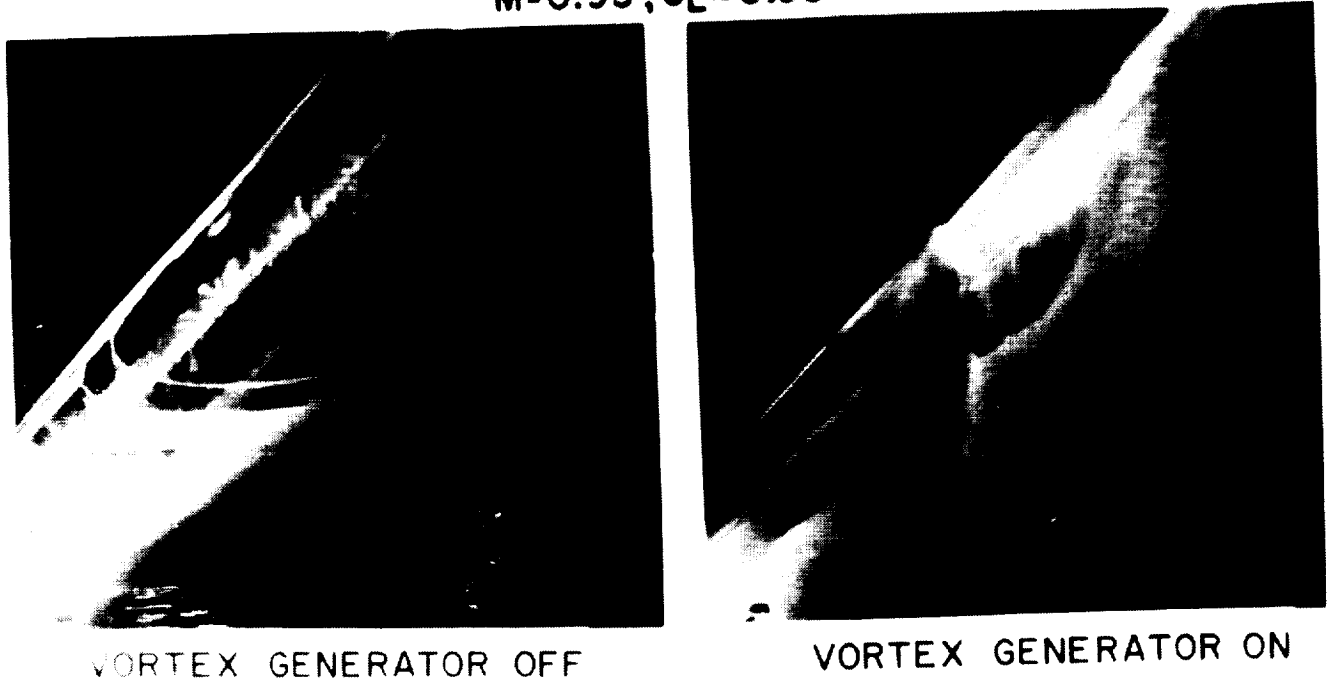


Figure 10. Oil flow, vortex generator effect ($M = 0.95, C_L \approx 0.93$).

That's all I'm going to say about things that happened up to the F-8 Supercritical Wing Program. I'd now like to say something about what happened immediately after that program. At that point we had a new administration at headquarters. George Low had moved back there. He was gung-ho for convincing the industry to apply the new wing on a real transport. At Langley, we tested the same wing used on the F-8 on an indented transport fuselage. Figure 11 shows a General Dynamics version of an actual transport.

ARTIST'S CONCEPT OF A NEAR-SONIC TRANSPORT INCORPORATING A SUPERCRITICAL WING

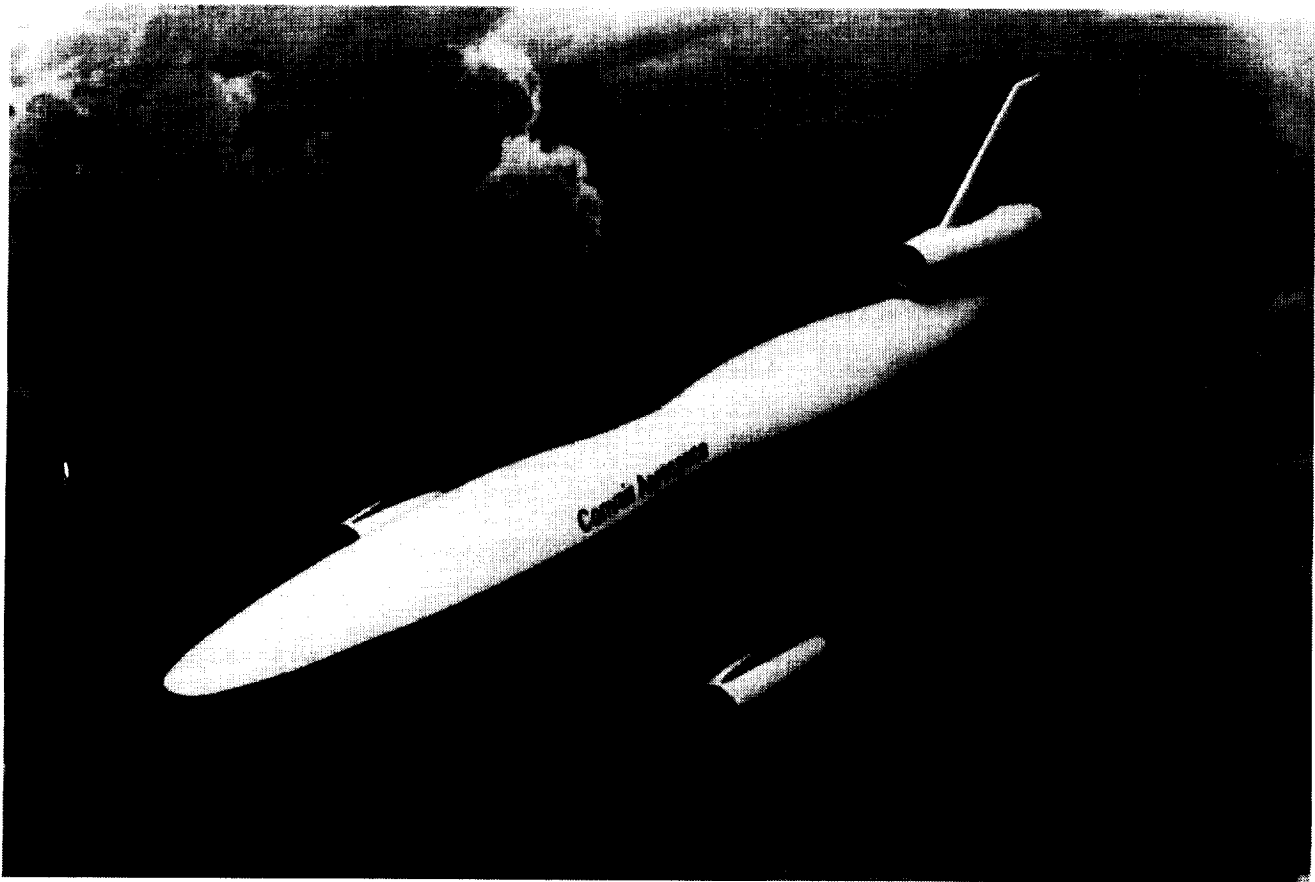


Figure 11. Artist's concept of a near-sonic transport incorporating a supercritical wing.

To account for the expansion of the stream tubes above the upper surface associated with the supersonic flow in that region, we altered the ideal area distribution for a supercritical body of revolution to the modified shape shown in figure 12. This resulted in a deep indentation of the fuselage. This configuration provided a cruise Mach number of 0.98. We provided the industry with the coordinates and aerodynamic data for this configuration. Three companies; Boeing, Douglas, and General Dynamics studied real transports based on this design. Boeing was so impressed with the results of their study that they started designing a production airplane based on the design.

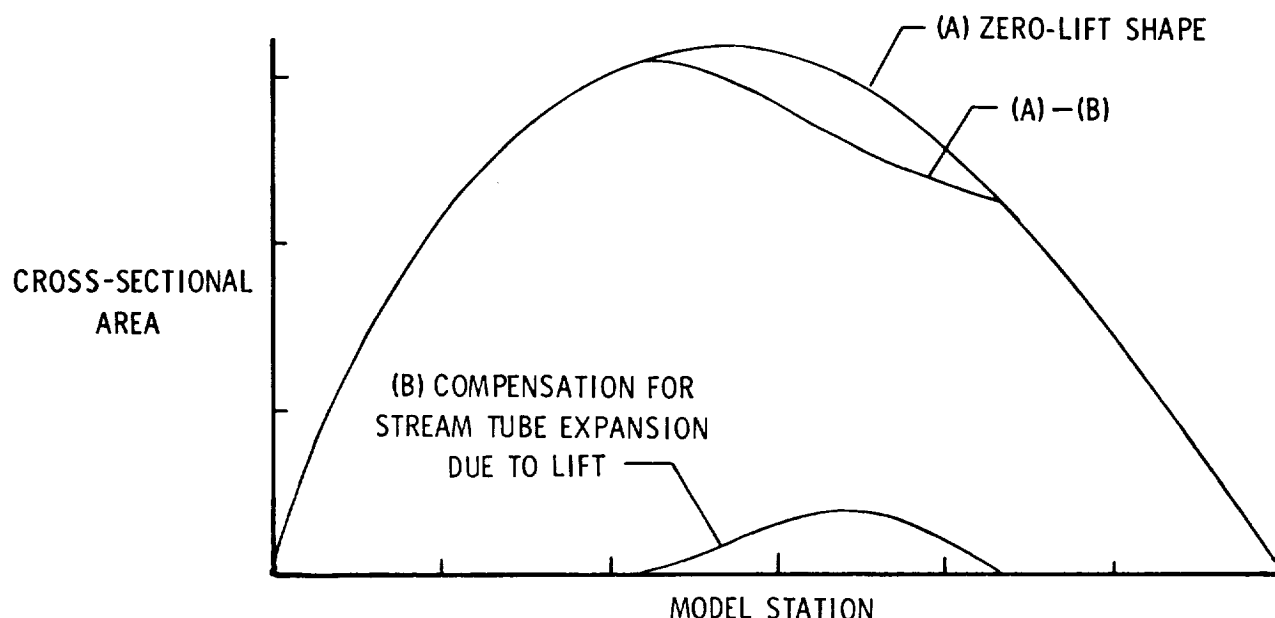


Figure 12. Second-order area-rule considerations.

Now I have a sad story to tell. About two months after that systems study was completed, the Arabs quadrupled the price of fuel and the airlines weren't the least bit interested in buying faster airplanes. They said, "Give us something that would reduce the fuel consumption." So we did two things. We used supercritical technology to obtain higher lift-to-drag ratios at the same speed as for existing airplanes rather than to increase the speed. This was accomplished by using thicker airfoil sections and a reduction in wing sweepback, both of which allowed an increase in aspect ratio without an increase in wing weight (a thicker supercritical wing had been demonstrated in flight using a Navy T2C trainer as a test bed). Most new transport airplanes today have high-aspect ratio-supercritical wings. We also started working on winglets.

Well, that is about my story, so if you have any questions, I'll be happy to answer them.

Audience: How about the Harrier AV-8B, is that supercritical?

Dr. Whitcomb: Oh, yes. The aerodynamics on the original British Harrier weren't too good. So Douglas Aircraft, which had a cooperative agreement with the British, put a supercritical wing on the Harrier. Now there are many airplanes with supercritical wings, but they're designed for $M = 0.8$ to 0.85 , not for $M = 0.98$ as was the wing for the F-8. The Douglas company for example has the supercritical wing on their new MD-11. I didn't want to say that the supercritical wing died; just this particular configuration on the F-8.

Audience: Do you remember back in 1970, Swearingen tried to build a supersonic jet? He spent \$35 million and went bankrupt.

Dr. Whitcomb: Of course he had to go bankrupt. He was wrong! I never talked to Swearingen, but I did talk to the aerodynamicist designing the airplanes who called me. I told him they were wrong. For an airplane the size of a business jet, with the long and narrow fuselage required for supersonic flight, everybody would have to lie down.

Audience: The General Dynamics people came to see you about an anti-shock body. I haven't heard that mentioned at all, can you say a few words about that?

Dr. Whitcomb: The anti-shock bodies did work. However, they basically accomplished the same aerodynamic effect as the supercritical airfoil, so they're not needed on a wing with these airfoils.

Audience: Do you know anything about supercritical wing development being done in the Soviet Union?

Dr. Whitcomb: No, I know nothing at all about that. I know that it has been used on the European Airbus. Phillipe Poisson-Quinton, a Frenchman called P.Q., came to see me during his regular visits to this country. Also Percy of Britain visited me. I told them, in general terms, what we were doing on the supercritical airfoils. However, I could not show them any wind-tunnel data since they were classified. The French and British then conducted wind-tunnel tests of their versions of the airfoil. P.Q. came back to show me some of their data. Later, several European papers on various aspects of supercritical wings were presented at an international conference in Haifa, Israel.

One of the things that we have in this industry is that, and it really drives you up the wall, there is a very strong anti-age factor. Ultimately they'll use the technology, but they drag their feet for years.

INTRODUCTION OF TOM McMURTRY

Ken Hodge

At the Pilot's Panel this noon we were making excuses for Tom McMurtry's absence. Tom is here now and we'll have his views on the supercritical wing in just one moment.

Tom is currently the chief of the Dryden Flight Operations Division. He's been a research pilot here for the last 25 years. His 10,000+ flight hours include service as the F-8 Supercritical Wing Project Pilot; he was also a co-project pilot on the Digital Fly-By-Wire airplane.

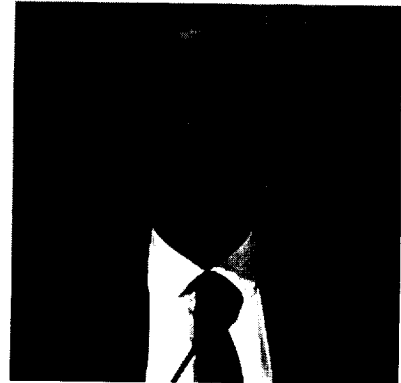
He's a former Navy pilot, Naval Test Pilot School graduate; his experience here at Dryden ranges from small-scale aircraft like the AD-1 up to being one of the project pilots on the 747 Shuttle Carrier aircraft. He's the recipient of the NASA Exceptional Service Medal for his work on the F-8 Supercritical Wing.

A PILOT'S VIEW OF SUPERCRITICAL WING

Thomas McMurtry

Twenty years, my how time flies when you're having fun!

I'm going to begin by showing you a short film that's been put together from some footage from the early flights of the F-8 Supercritical Wing airplane. Before the film begins, I want to suggest that you carefully note how the pilot pulls and tugs on the engine inlets and the wheel well doors during his walk around pre-flight. I suppose that those things could fall off some time! Also note how the pilot describes the flight after getting out of the airplane. Pilots have to use their hands for something! I'll make a few comments as the film is shown.



The first take-off was made on the dry lake bed at Edwards. One of the great features of the Dryden Flight Operations area is the availability of the lake bed for unique take-offs and landings. During the flight program we did a lot of maneuvers such as pull-ups, push-overs, etc., to determine the stability of the airplane. Most of the footage in the film was shot during the first few flights of the airplane. We used F-104s as chase airplanes. Later in the program, there were times when the F-8 Supercritical Wing and the F-8 Fly-By-Wire airplanes flew at the same time. I think the F-8 Supercritical Wing airplane is a beautiful airplane when in flight. The first landing was made on the lake bed. The airplane was very stable during the approach and landing.

In the interest of accomplishing the first flight on the airplane as soon as possible, the airplane was not painted in the blue and white scheme as it is today. There was no time or money to do that! The SCW symbol was actually taped on the tail of the airplane for the first flight. Would you believe it? A picture of the airplane in this configuration made the cover of Aviation Week. There were some interesting features on the F-8 Supercritical Wing airplane, and I'll describe them to you today.

To fair the fuselage glove into the forward fuselage, an extension over the rear part of the canopy was added. This extension was called the "cape" and it had to be installed after the pilot was in the airplane, and after the canopy was closed. Also it had to be removed before the pilot opened the canopy after flight. It extended over the canopy about 18 in. and was designed to tear away with canopy separation during ejection. We never did test for separation, but we did the analysis to determine that it would not degrade the capability of the ejection seat in the airplane.

Since the wing was designed to carry no fuel, there was 4,700 lb of fuel in the airplane at engine start. This resulted in flights of approximately 1 hr when afterburner was not used. No aerial refueling capability existed in the airplane. For higher lift, the ailerons were drooped 20°; this was to provide higher lift for take-offs and landings. The speedbrake was on the lower fuselage. It could be extended 15° for landings to increase the drag of the airplane to allow better engine response if a go around was required.

Now I'll talk about the handling qualities of the airplane. Remember that the intent of the F-8 Supercritical Wing Program was to demonstrate the applicability of the concept to a transport-type airplane. Even though the F-8 didn't look like a transport airplane, it was thought that maneuvers could be performed to simulate a transport airplane. The handling qualities were thus looked at as to their acceptability for a transport airplane.

A concern about take-offs and landings was the fuselage incidence angle. The basic F-8 airplane had a two-position wing; one position for take-offs and landings and the other for cruise. Only the cruise position was retained on the F-8 Supercritical Wing airplane. Over-rotation could easily cause the tail to strike the ground. To prevent this from happening, a reference pitch attitude was proposed for the pilot. To determine this, we jacked the plane up before the first flight, with the pilot in the cockpit. We measured the clearance between the fuselage tailpipe and the ground and when it equalled 1 ft we placed a mark with grease pencil on the forward wind screen that was used as a reference by the pilot so that he didn't over-rotate the airplane during take-off or landing and thus strike the tail on the ground. You might consider this crude, but remember this was a low-cost program and the idea worked because we never scraped the tail.

During take-off the airplane handled quite well. Nosewheel steering was used until about 75 kts, at which time directional control effectiveness became quite good. Pitch control was responsive with no tendency to over-control. As mentioned earlier, the first take-off was made from the dry lake bed. Later take-offs were made from the hard surface runway toward the lakebed. During climb-out, the airplane handled quite well. Test maneuvering was performed to represent a transport airplane. Dick Whitcomb commented about a concern about the pitch-up characteristics. During my experience flying the airplane, I never experienced any pitch up. We did fly the airplane up to about 20°-angle of attack and the problem that we encountered there was that we started to get roll-off that we couldn't control with the airplane lateral controls. We didn't go into a stall but we went to the angle of attack where we lost lateral control.

At the cruise conditions, the airplane was quite stable. The airplane could be quickly established at a test condition and easily held there. One of the concerns was that with the transport airplane, if you had an upset, and the airplane attained a very high speed, was there going to be a problem recovering the airplane? We investigated that and determined that any upsets of the airplane would be easy to control.

No high-g maneuvers were performed. The airplane was limited to +4 gs. Approaches were flown at approximately 170 to 175 kts. Control on all axes was very good; engine response was good. The landings were not made with standard Navy F-8-qualified tires, because the original F-8 tires were rated up to only 178 kts. The F-104 tires were used on the F-8 Supercritical Wing wheels and were qualified for speeds up to 239 kts. Landings were made on the dry lake bed because there was no anti-skid brake system on the airplane.

There were 11 pilots who flew the F-8 Supercritical Wing airplane for a total of 86 flights. The results of the flight program compared very favorably with the results from the wind tunnel.

Looking back, I believe that the testing team was highly motivated because everyone knew that a successful flight-test demonstration would result in applicability of the concept to the benefit of future transport airplanes. With the best test team at work on the project, it was fun, exciting, and successful.

Thank you very much.

INTRODUCTION OF JAMES A. BLACKWELL

Ken Hodge

We turn once again to the Aerospace Industry to find out the influence the Supercritical Wing airplane has on today's aircraft. Our speaker will be James Blackwell, better known professionally as "Micky" Blackwell.

During the past 18 months, he has been the F-22 Program Vice President and General Manager at the Lockheed Aeronautical Systems Company in Marietta, Georgia. Previous to that, he was vice president and general manager for the Lockheed portion of the Advanced Tactical Fighter Program. He joined the company in 1969 as a research engineer after working at NASA Langley for Dick Whitcomb. He's held a number of management positions at the Georgia company including engineering program manager for special projects for staff aeronautics, and vice president of engineering.

In 1987 when one of the Georgia companies merged with the California company, he became vice president and general manager of Research Technology and Engineering. More than an adequate background to comment on the supercritical wing.

INFLUENCE ON TODAY'S AIRCRAFT

James Blackwell

The greatest heritage that NASA has is its people, facilities, and resources. It's people like NASA's Dick Whitcomb that make this country great. His life has been focused. Working first as an aerodynamics research engineer and later as the branch head of the Eight-Foot Tunnel Transonic Aerodynamics at Langley, he has dedicated his life to improving aircraft aerodynamics, improving that science that he loves so well. All that I have learned about the practical application of aerodynamics I learned from Dick Whitcomb. I hope that each of you have the good fortune in your career to be able to work with someone as outstanding as Dick Whitcomb.

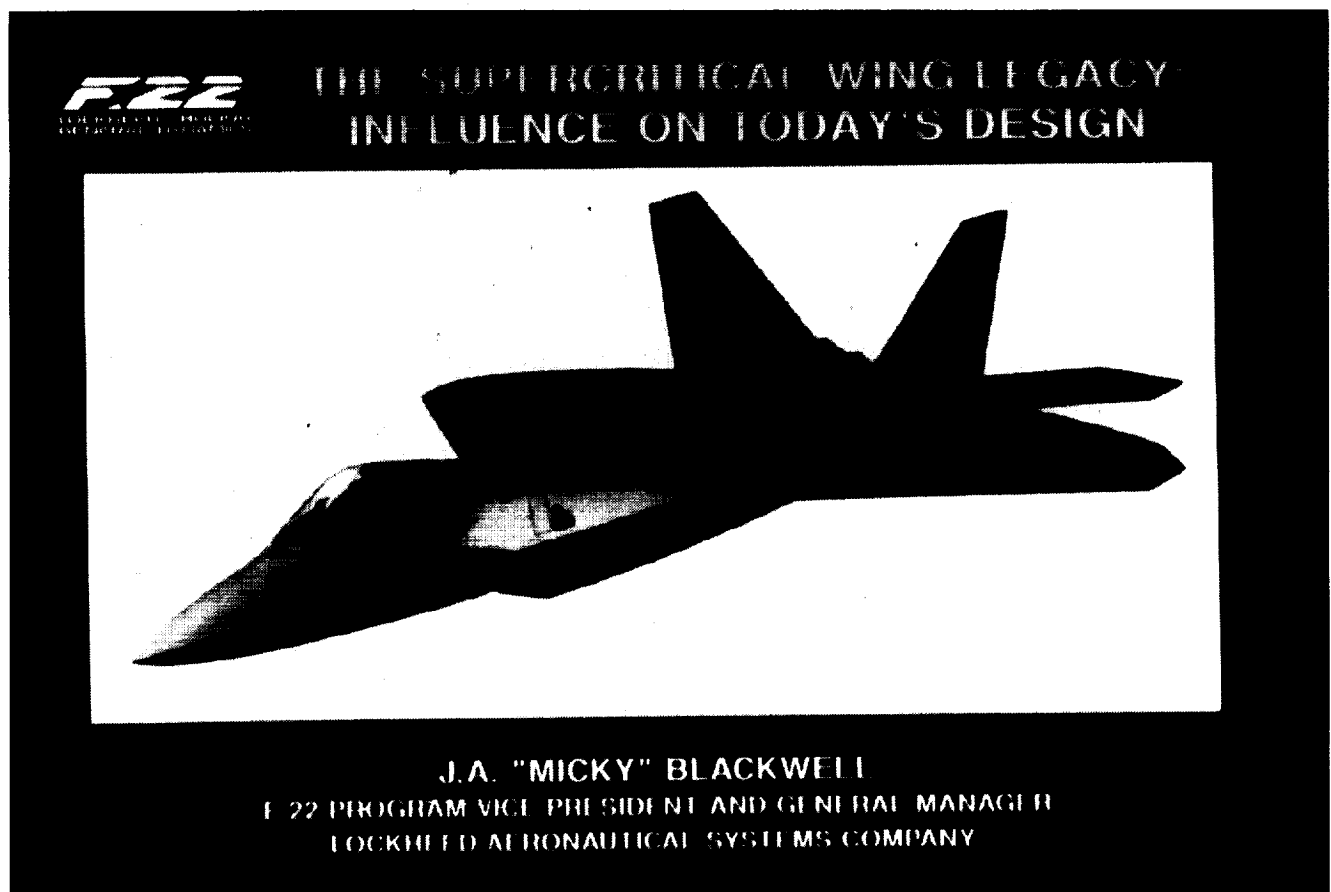


Figure 1. The Supercritical Wing Legacy: influence on today's design.

As indicated in figure 1, I would like to talk about the influence on the design of today's aircraft that supercritical technology has had. Today, we see a lot of different kinds of applications. Even before I left

NASA in 1969, supercritical technology and its principles were being used in numerous applications (e.g., fighter wings, transport wings, helicopter rotors, engine blades).

As shown in figure 2, I'm going to talk about the influence of supercritical technology on one of the most complex airplanes that we're building today—the F-22, the US Air Force's new air superiority fighter. I'll also take the liberty to talk about other technologies that NASA has developed and the influence that they have left on the F-22 Program. Finally, I'll show you where the F-22 Program stands today.

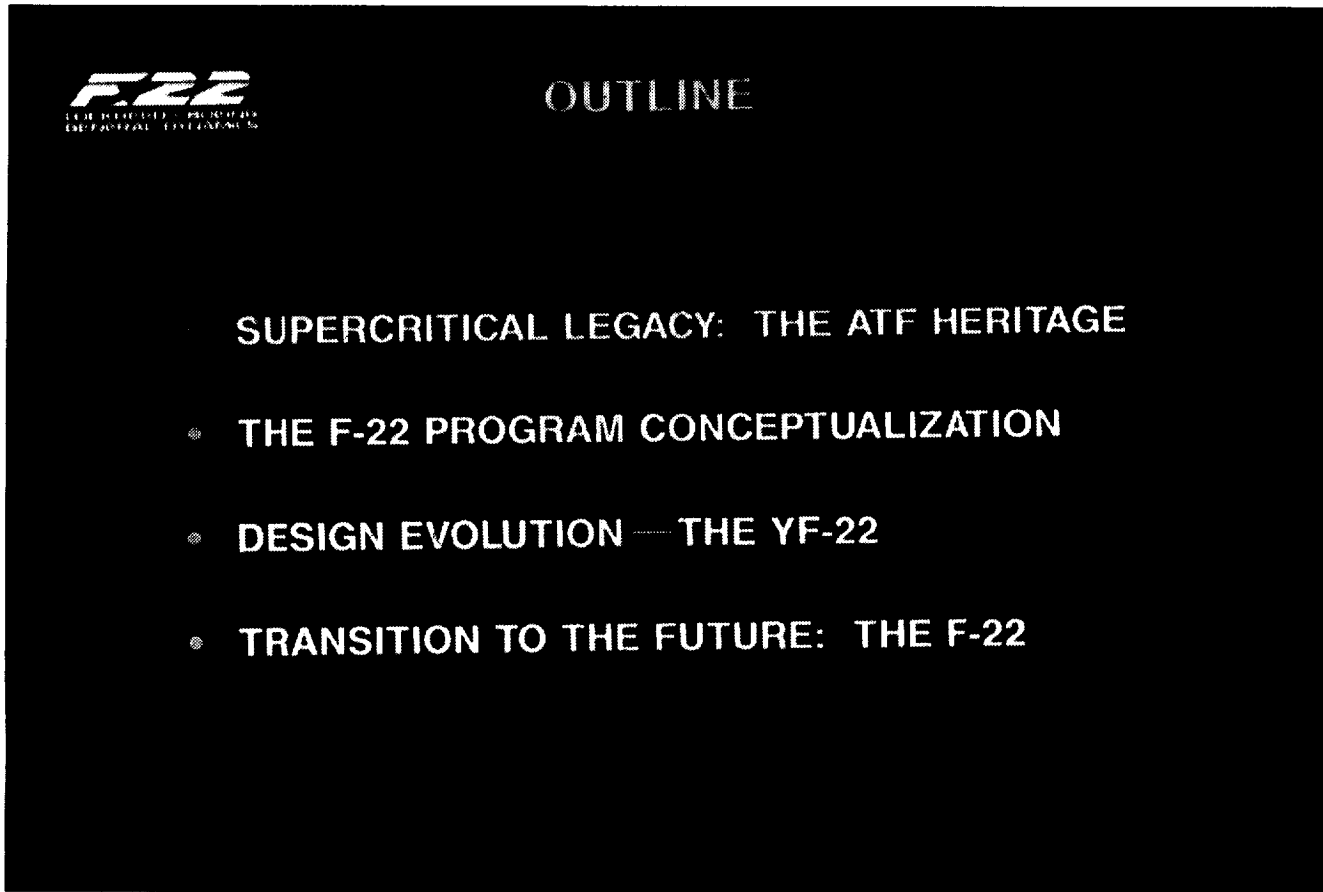


Figure 2. Outline.

The heritage of supercritical technology shown in figure 3 started in the 1960's. Supercritical flow technology development gave the whole industry the possibility that major improvements in transonic aerodynamic performance could be made. Key on that word "possibility," because unless you believe that it's possible to discover, you won't be able to discover at all. Dick Whitcomb grasped that possibility and the major achievement that he gave to us was the understanding of transonic-supercritical flow—what made it tick, how it worked, what you had to do physically and logically to come out with a superior-performing airfoil.

AERONAUTICAL TECHNOLOGY ADVANCES

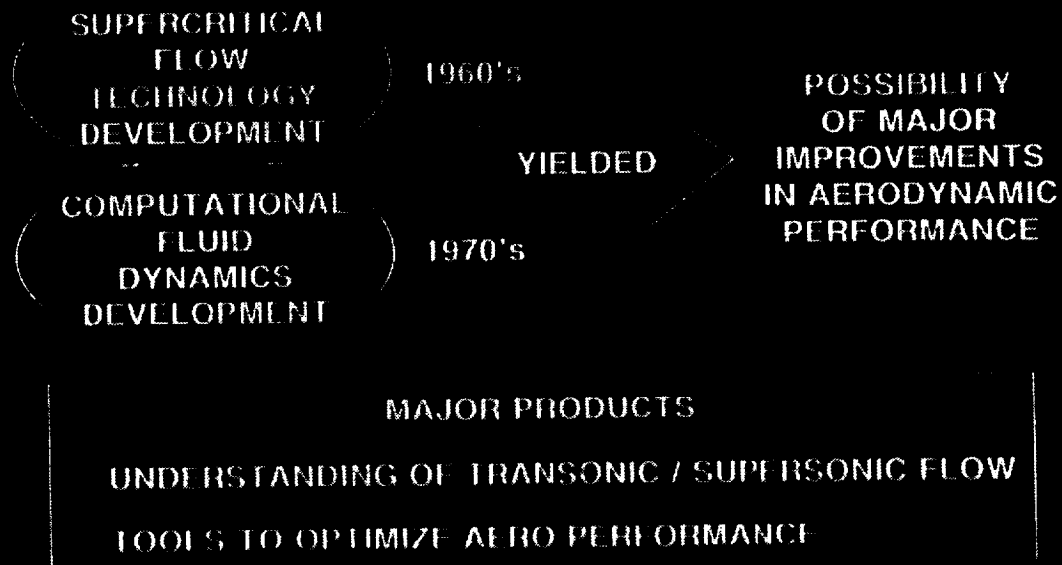


Figure 3. The heritage: aeronautical technology advances.

In an earlier presentation, Dick Whitcomb discussed how we used the primitive airfoil design and analysis tools that existed in the late 1960's to work in the transonic flow regime. It was not until the 1970's, after we understood that possibility of tremendous improvement in transonic aerodynamics that the computational tools began to catch up. By the early 1980's, we had the technical understanding of supercritical flow concepts plus we had the computational tools to optimize that aerodynamic performance of all kinds of airplanes, including fighters, transports, helicopters, and even engines.

One small humorous tidbit about application of supercritical flow technology to fighters. Dick Whitcomb was asked in the mid-1960's to apply the supercritical airfoil to the F-14. Subsequently the Navy came out with a written proclamation that the contractor could not use supercritical airfoils on the F-14 because they were "supercritical" and, therefore, they must be "super sensitive!"

Fighters have come a long way since the F-14; the NASA technology advances that have influenced the F-22 are shown in figure 4 and are more than just the aerodynamic advances. NASA has spent millions of dollars on composite materials helping industry in understanding how to design composites. All of this technology has gone into the F-22. The same thing goes for the fly-by-wire flight control system lessons-learned in the design of the F-22. NASA has also been in the forefront of stealth technology. A considerable amount of the F-22's stealth design has benefitted from NASA's research work.

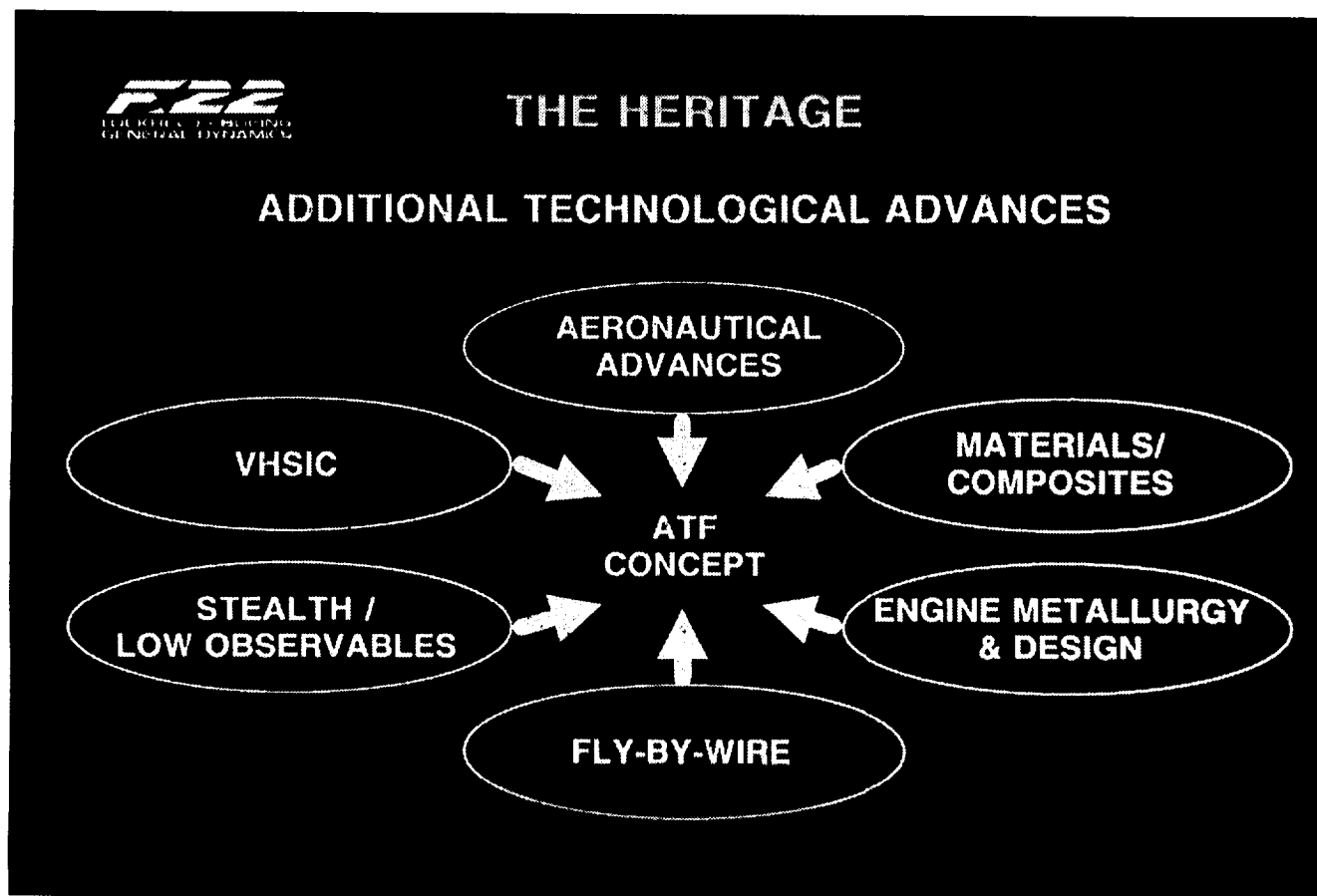


Figure 4. The heritage: additional technological advances.

So as you can see, there were many NASA technologies in addition to supercritical flow technology that have influenced the design of the F-22.



Figure 5. F-22 major events.

The influence of supercritical flow technology on the F-22 started during the Advanced Tactical Fighter (ATF) demonstration and validation program which began on October 31, 1986 (fig. 5). Northrop and Lockheed were engaged in a fight to the death that began in October of 1986 and ended in April of 1991. Lockheed won the opportunity to begin the engineering and manufacturing development (EMD) program for the F-22.



F-22 TEAM SYSTEM DESIGN OBJECTIVES

BALANCED SYSTEM DESIGN

- LETHAL
- SURVIVABLE
- SUPERCRUISE
- MANEUVERABLE
- RELIABLE, MAINTAINABLE, SUPPORTABLE
- AFFORDABLE FLYAWAY COST
- GROWTH POTENTIAL

AERODYNAMIC FIDELITY BETWEEN YF-22 AND F-22

Figure 6. F-22 team system design objectives.

It was during the dem/val program that we developed our strategy of how to design the F-22 using all of the concepts and the technology that we have just discussed. The F-22 had to be a balanced system design. The characteristics of the balanced design are shown in figure 6. There has never been an airplane more integrated than the F-22. Every technology touched another technology.

The F-22 had to be lethal, carry sufficient weapons, and carry them internally. The weapons had to be carried internally because you could not supercruise if you didn't. This airplane is roughly the same size as the F-15. However, the F-22 had to absorb inside the fuselage all the missiles and all the fuel carried externally by the F-15. Additionally, it had to be roughly the same weight as an F-15, and it had to have better performance. It also had to be highly maneuverable. This airplane was designed to have an unlimited angle of attack so that it could fly at 90° to the wind. It had to be reliable, maintainable, and supportable. Every capability put on the airplane had to be balanced against cost and judged to be a good trade-off.

Lastly, our strategy required a high degree of aerodynamic fidelity between the YF-22 airplane prototype, built and tested during dem/val, and the F-22 we wanted to build in EMD. We wanted the huge dem/val program database developed over four years to be carried forward and used to reduce EMD program risk.

One reason for flight testing in a dem/val program is risk reduction. This requirement came as a result of the Packard Commission. The Packard Commission recommendations are reflected in how the F-22 dem/val program was structured. The dem/val program consisted of the five parts shown in figure 7: (1) systems specification development - we had to work with the Air Force to develop a balanced design that met the Air Force's systems requirements and could be produced with low technology risk; (2) we had to prototype the F-22 avionics and demonstrate their performance in flight; (3) we had to validate the stealth characteristics of the aircraft; (4) we had to prototype the engine; and (5) we had to prototype the aircraft itself for flight test to demonstrate the flying prototype performed as advertised.

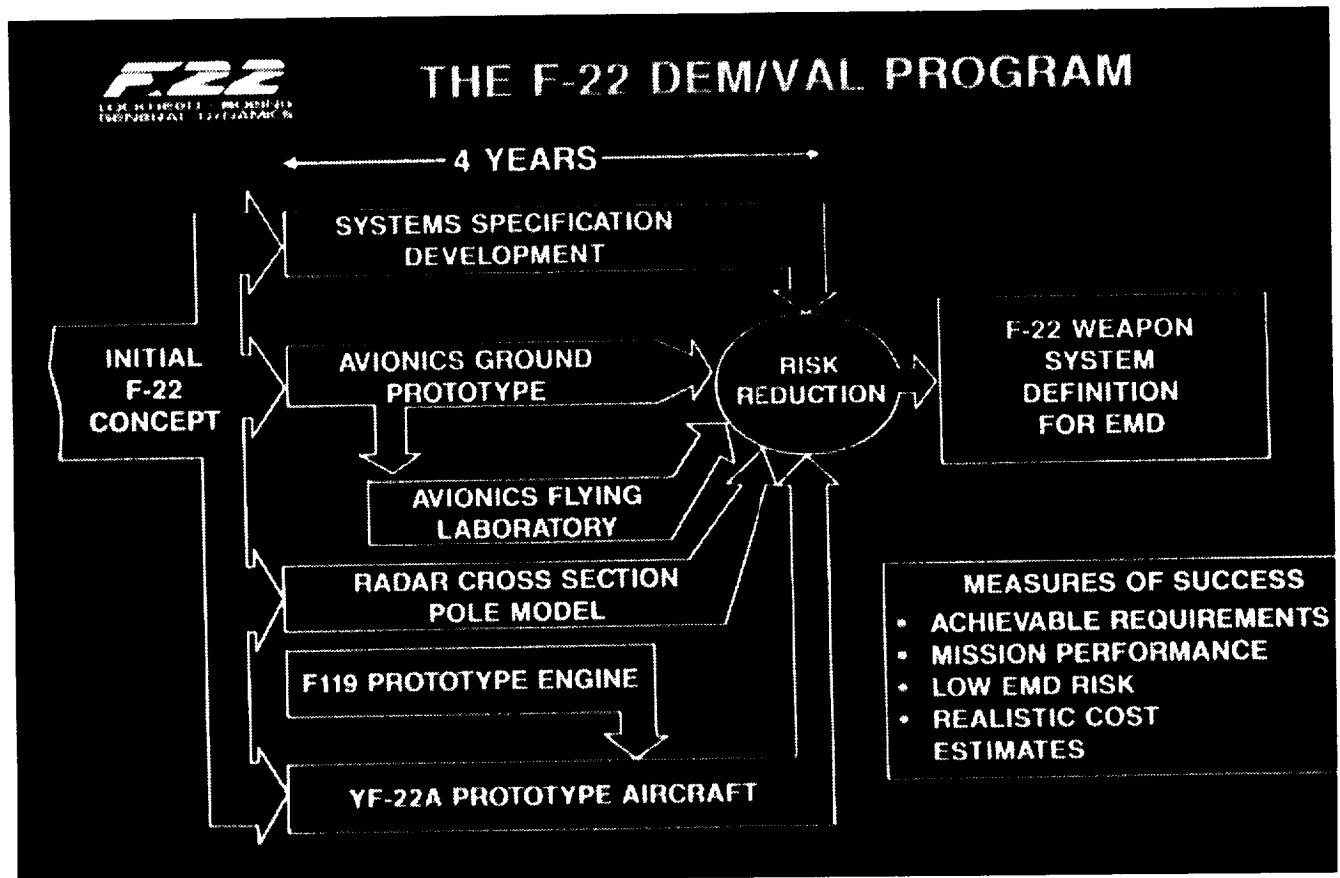


Figure 7. The F-22 dem/val program.

All of the previously mentioned items added up to four years of invention and discovery and bringing technology to low risk. We started the engineering/manufacturing development phase in August of 1991. Our focus in this phase is on the implementation of existing technology and not discovery of new technology.

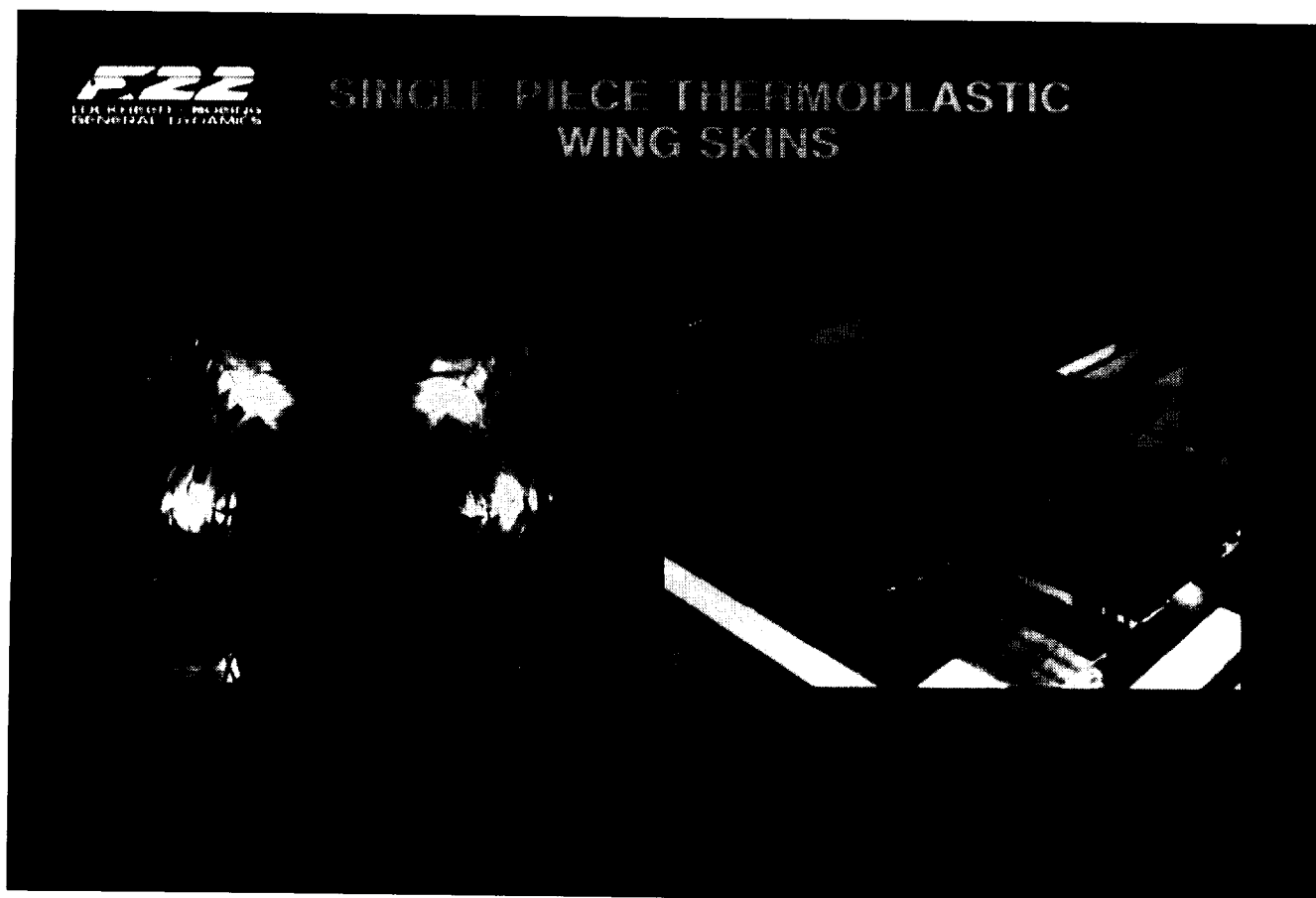


Figure 8. Single-piece thermoplastic wing skins.

One of the dem/val technology activities is illustrated in figure 8 and happens to be the largest composite thermoplastic wing that has ever been built. It uses a lot of composite technology that was developed at NASA. This work is typical of the kinds of technology development we have done to implement advanced technologies and bring the technologies to low risk.

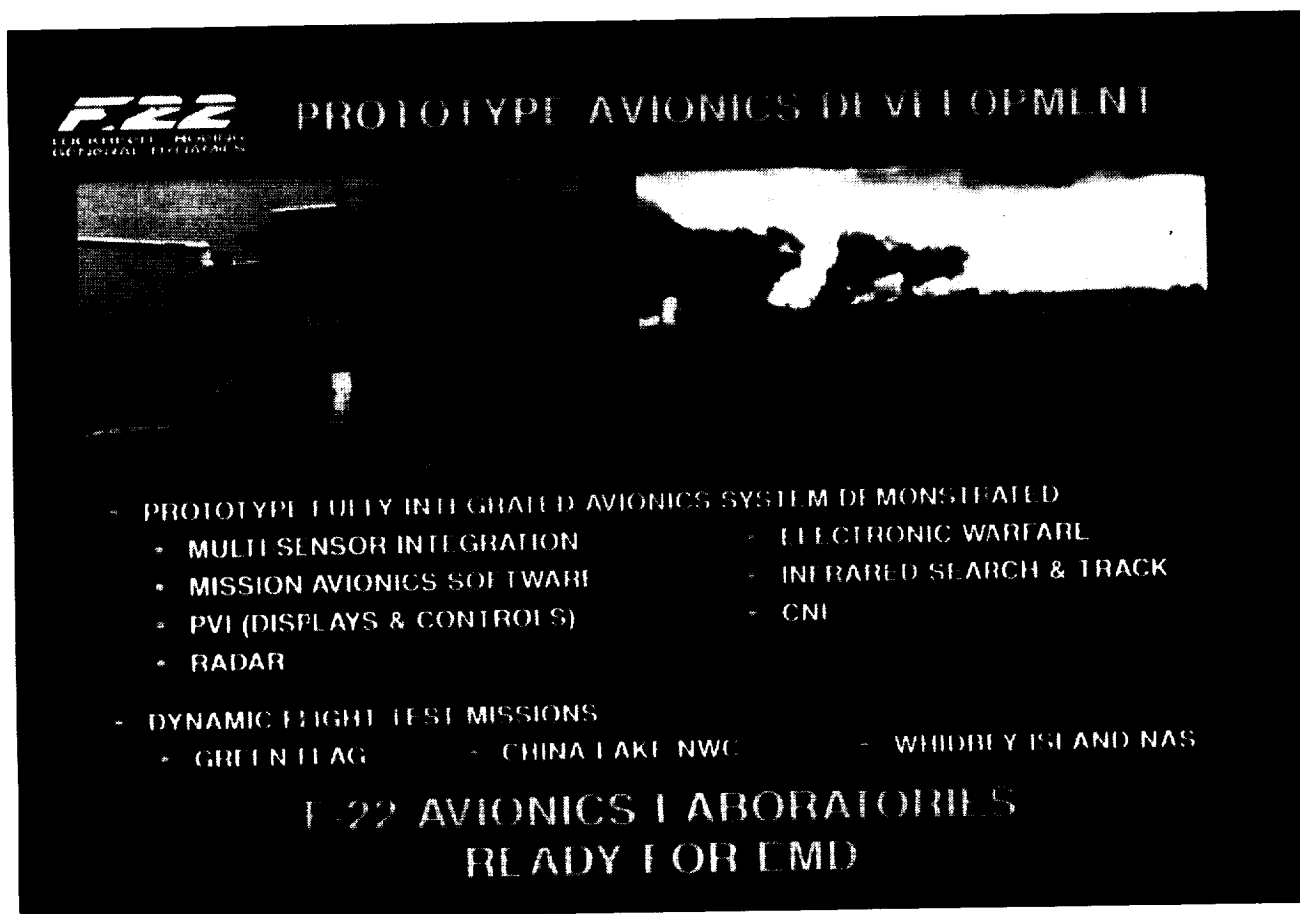


Figure 9. Prototype avionics development.

Figure 9 is another example of applying advanced technology to the F-22. Many of the technology risk reductions were demonstrated in flight test. We took the avionics sensors developed in dem/val and integrated them in our avionics test facility located at Boeing. It took over 100 VAXs in this facility to integrate all the sensors. We took the results of the ground tests and installed the avionics in the 757 avionics flying test bed. We successfully demonstrated sensor fusion in flight.

F22
LEW KIRCHGESSER
INTERNATIONAL TYPEFACER

RADAR CROSS SECTION POLE MODEL

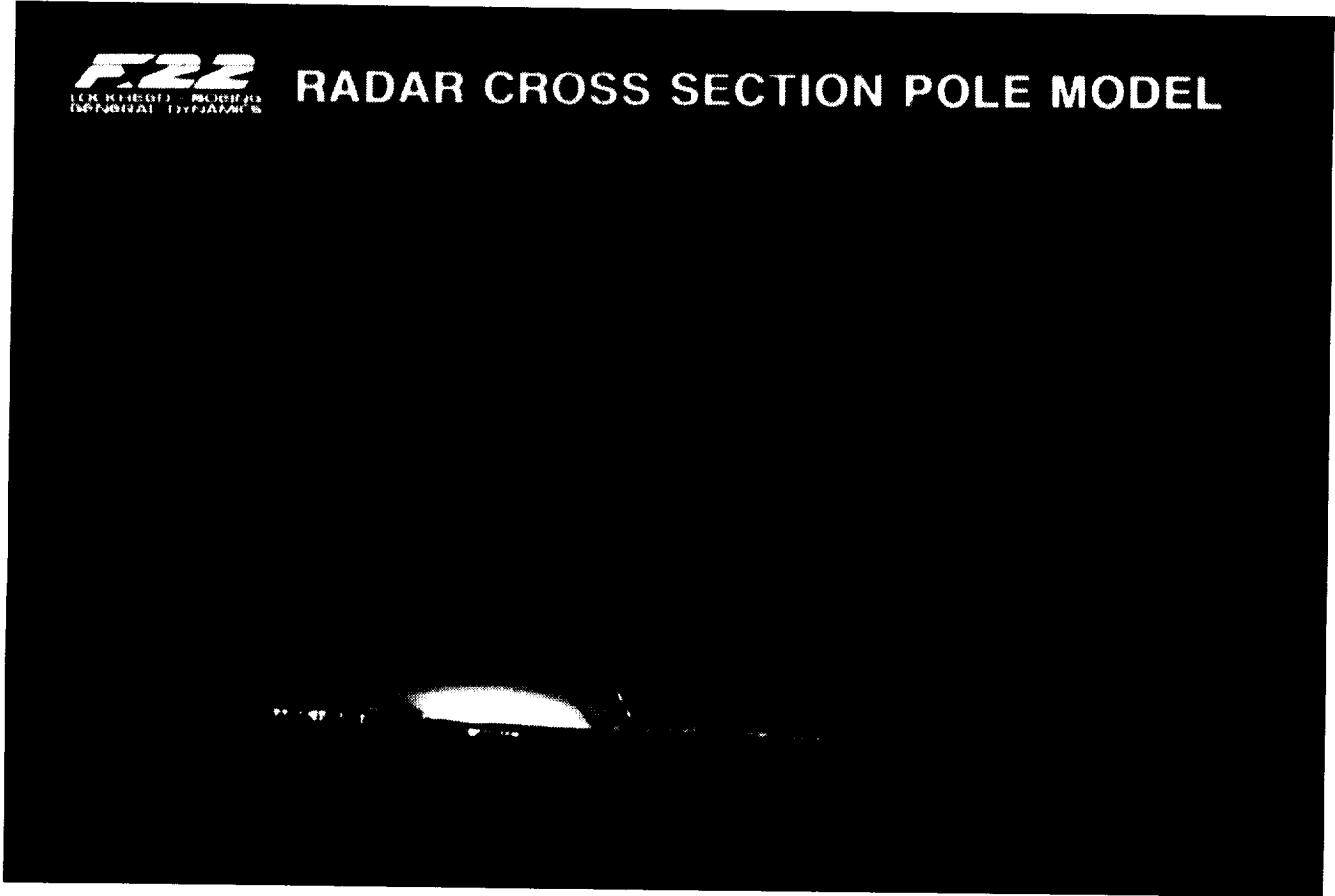


Figure 10. Radar cross-section pole model.

In figure 10, a full-scale radar cross-section pole model is shown out in the desert, not too far from Edwards where we successfully demonstrated the blending of stealth technology and aerodynamics. Most of you have seen the F-117 in flight—remember, the F-22 also has to be stealthy and, in addition, has to have maneuverability that far exceeds the F-15.

**CONFIGURATION SHOULD HAVE UNLIMITED AOA AND
GOOD CONTROL POWER**

**AREA RULE SHOULD BE OPTIMIZED AT LOW LIFT TO
ACHIEVE SUPERCruise**

**CONFIGURATION SHOULD HAVE GOOD SUBSONIC
CRUISE AND MANEUVERABILITY**

**AERODYNAMIC SHAPING MUST BE CONSISTENT WITH
LOW OBSERVABILITY**

**DESIGN MUST HAVE REDUNDANT CONTROL SURFACES
FOR SURVIVABILITY**

Figure 11. Aerodynamic design guidelines.

Let's look at the YF-22 prototype configuration development and how supercritical technology was applied. First there were some aerodynamic design guidelines (fig. 11) that we wanted to apply. We wanted a configuration that had an unlimited angle of attack and good control power. The aircraft had to be area-ruled so we could achieve supercruise. We also had to have good subsonic cruise and maneuverability. The aerodynamic shaping had to be consistent with low observability. Finally, the design had to have redundant control surfaces for survivability.



CONTINUOUS IMPROVEMENT THROUGH DESIGN EVOLUTION

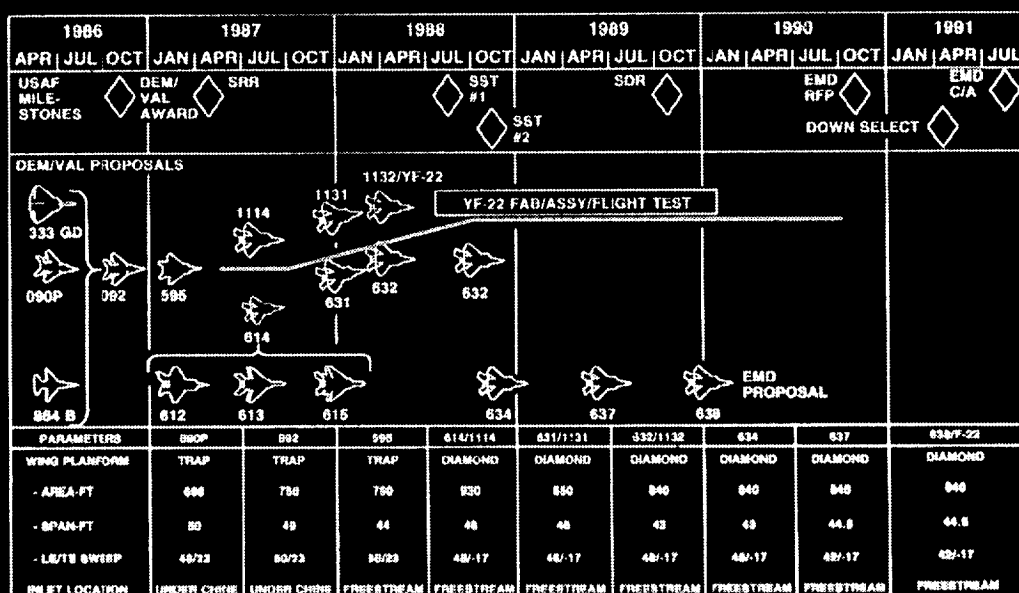


Figure 12. Continuous improvement through design evolution.

The development of the F-22 airplane configuration started with a great deal of design diversity. The airplane team was made up of Lockheed, Boeing, and General Dynamics. The dem/val proposal configurations from each of the three companies are shown on the far left of figure 12. After Lockheed had won, and the other two became partners, we then shared data and out of that came the starting point which is referred to as 092.

We made two major configuration changes as we proceeded from 092 to our EMD proposal configuration 638. The first change was made in early 1987. We changed the inlet locations from under the fuselage chine to side of body. The second significant change occurred in mid-1987. We changed from a trapezoidal wing planform to a diamond wing planform. At this point, we had to carry two parallel designs: a design for the prototype to fly and a second design for our EMD proposal that would evolve later. The wing design tools we had at our disposal in 1984 were really quite robust. We had 3-dimensional analysis codes, inverse design codes, and constraint optimization design codes that came from NASA Ames. For the F-22 wing design we ran a "camber-off." All three F-22 partner companies, using different design tools, designed candidate wing configurations which were tested and the best was selected.

WING DESIGN APPROACH

ADVANCED DESIGN CFD METHODS

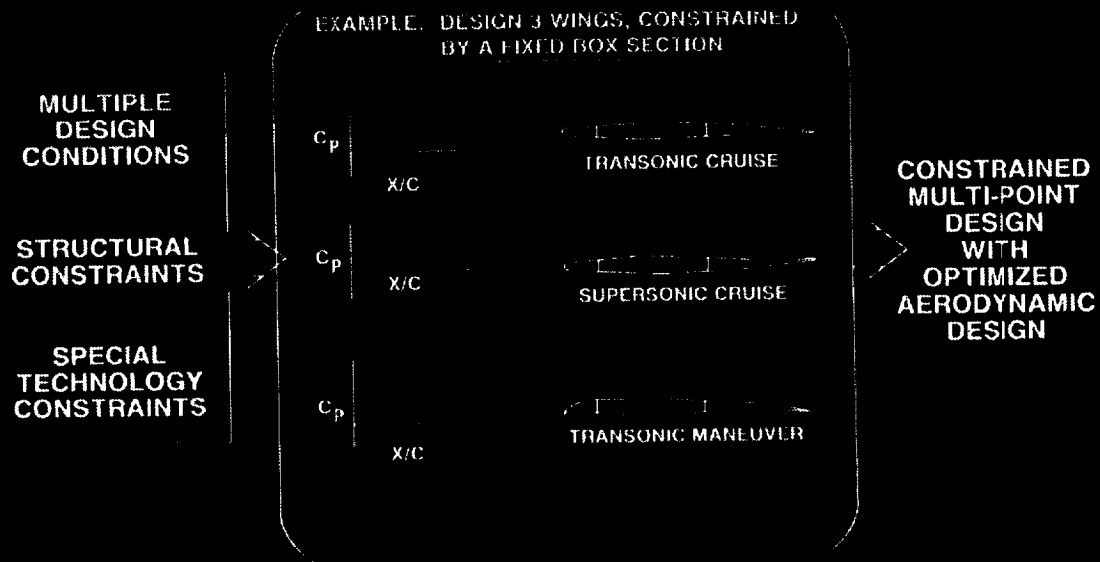


Figure 13. Wing design approach.

Figure 13 shows the constraints used in the wing design. The influence of supercritical technology is obvious in these constraints. A starting premise was that the lowest weight possible would be obtained with a common structural box design that used variable surfaces on the leading and trailing edges to optimize the aerodynamic characteristics for transonic cruise, subsonic/supersonic cruise, and transonic maneuvers.



WIND TUNNEL TEST PROGRAM

	TEST HOURS
PRIOR TO DEM/VAL	7005
DEM/VAL - YF-22	
- LOW SPEED STABILITY AND CONTROL	6715
- PROPULSION AERODYNAMICS	5405
- HIGH SPEED DRAG AND S&C	4000
- WEAPONS	700
- FLOW VISUALIZATION	695
- AIR DATA	240
- PRESSURE MODEL	95
- FLUTTER	80
SUBTOTAL	17,930
TOTAL	24,935

Figure 14. Wind-tunnel test program.

Good aerodynamic performance did not come cheaply. Getting ready for our dem/val proposal in 1984 and 1985, we used 7,000 hr of wind-tunnel test time as shown in figure 14. In the dem/val program, we used approximately 18,000 hr of wind-tunnel time covering low-speed stability, propulsion integration, high-speed drag, weapons release, etc. Northrop spent about the same amount. A great deal of our testing was done in NASA facilities. In the current EMD program, we're now scheduled for 13,000 hr of wind-tunnel testing.

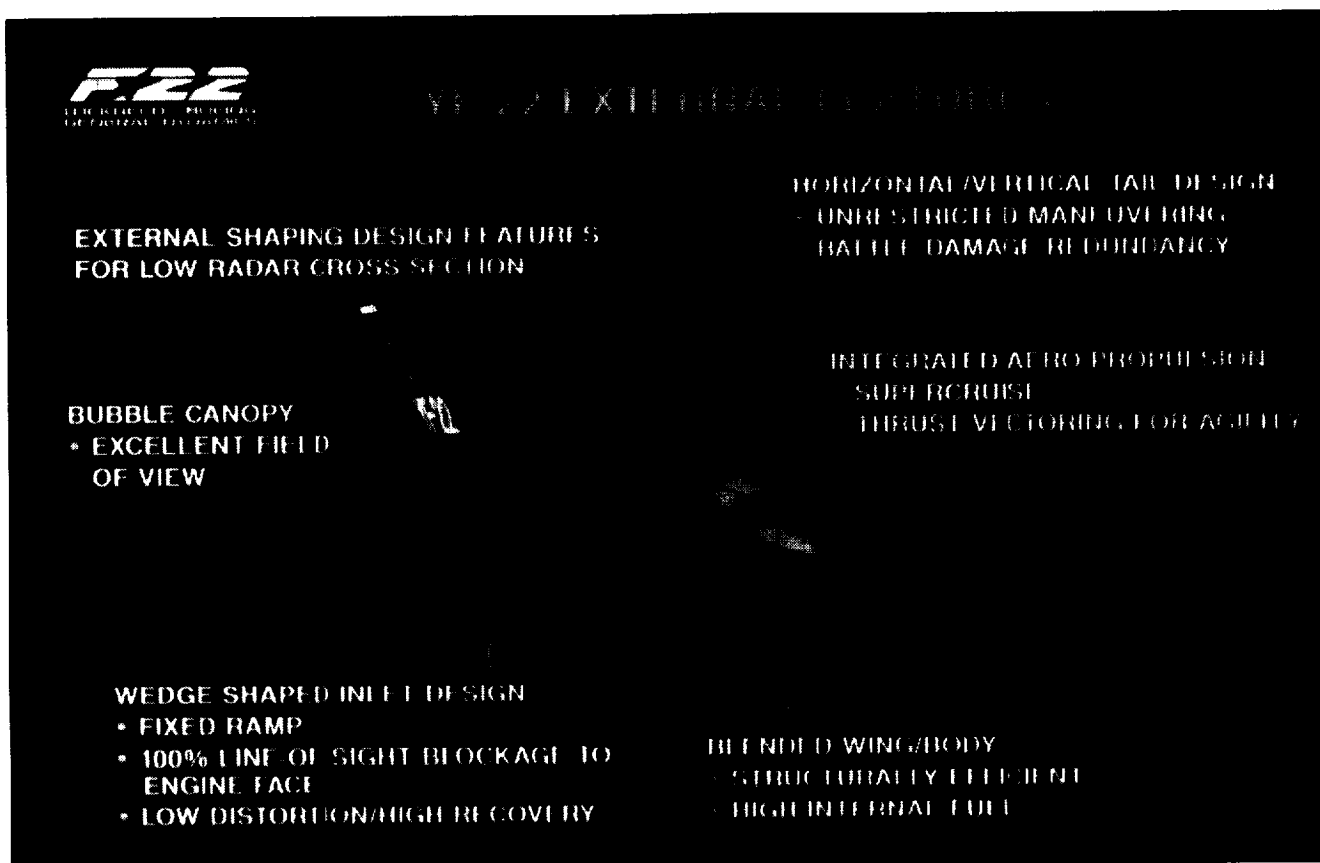


Figure 15. YF-22 external features.

The airplane shown in figure 15 is the result of the prototype (YF-22) design effort. The airplane has an angular appearance. It employs the same stealth principles as the F-117. We had to make sure that we matched the shaping from the stealth constraints and the shaping of the aerodynamics. The horizontal and vertical tail configuration on the airplane gave us the maneuverability we desired. We also have leading- and trailing-edge flaps and thrust vectoring nozzles on the airplane. The blended wing body is used for internal fuel and weapons carriage. The excellent inlets with very low distortion provide for thrust recovery even at very high angles of attack.

YF-22 DEMONSTRATION PROGRAM

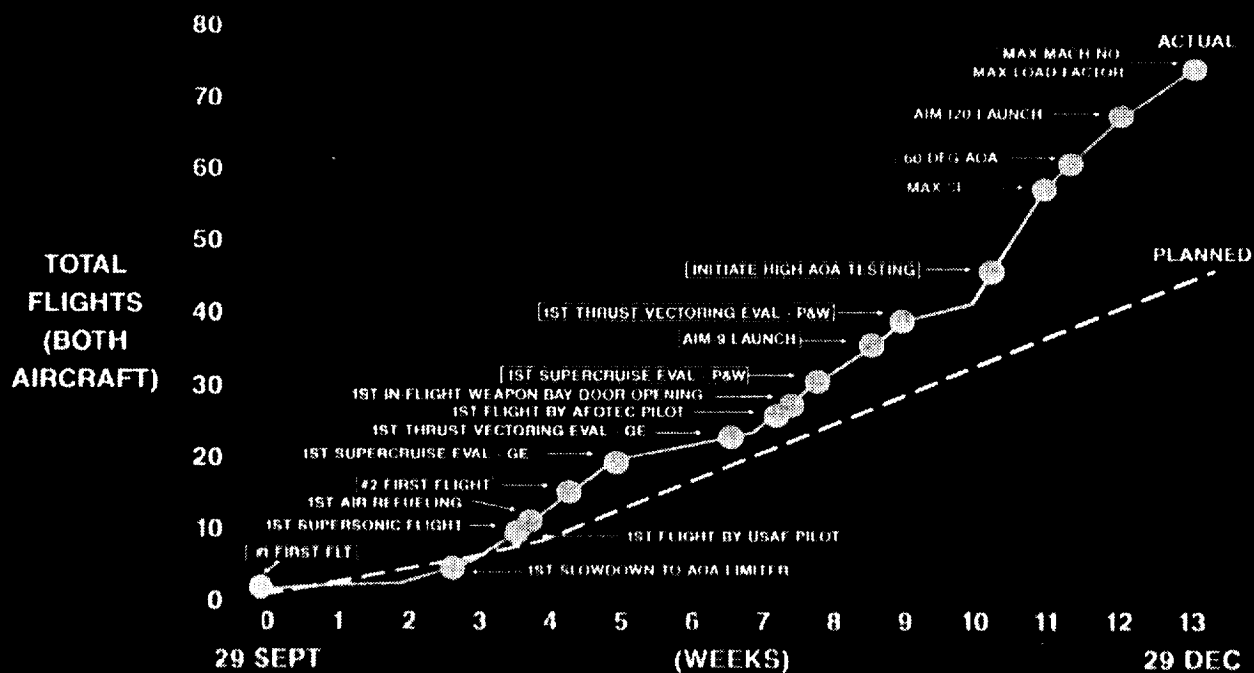


Figure 16. YF-22 demonstration program.

Figure 16 provides a snapshot of our YF-22 flight test program. We took three years and nine months to design, build, and get the YF-22 ready to start flying. The only requirement that we had in the dem/val contract for the prototype was to take off. Contractually, we didn't have to land the aircraft! Also, it was strictly up to the contractor as to how much flight test data he wanted to produce. We had from the 29th of September 1990 to the 29th of December 1990 to gather the flight data to put in our EMD proposal. It was a magnificent effort. The amount of data collected in this short time period was historic.



TRANSITION TO THE FUTURE THE F-22 EMD PROGRAM



Figure 17. Transition to the future: the F-22 EMD Program.

The transition to the F-22 EMD (fig. 17) is based on our successes in dem/val.



F-22 SIMILARITY TO YF-22 REDUCES LMD RISK

	F-22	YF-22	F-22	YF-22
LENGTH-FT	62.5	64.5		
PLANFORM	MODIFIED DIAMOND	MODIFIED DIAMOND		
WING			F-22	YF-22
AREA - SQ FT	840	840		
LE/TE SWEEP	42/-17	48/-17		
SPAN - FT	44.5	43		
TAIL AREAS - SQ FT				
HORIZONTAL	68	67		
VERTICAL	89	109		

Figure 18. F-22 similarity to YF-22 reduces EMD risk.

Now I want to show you the comparison between the YF-22 and the current F-22 configuration. Remember that one of our strategies was to make sure that there was a high degree of fidelity between the prototype airplane and the airplane we wanted to build in EMD. You can see in figure 18 that the YF-22 and F-22 configurations are indeed similar.

In conclusion, you have seen the influence of NASA's supercritical flow technology, as well as other NASA technologies, on the F-22 program. All of the technology, in one way or the other, has contributed to an outstanding, balanced fighter aircraft design (fig. 19). Every Air Force pilot that has flown the airplane thinks that it's an outstanding airplane. It has achieved through demonstrated performance all of the requirements that the Air Force had set forth. Today, ten months after EMD go-ahead, the F-22 program continues on track.

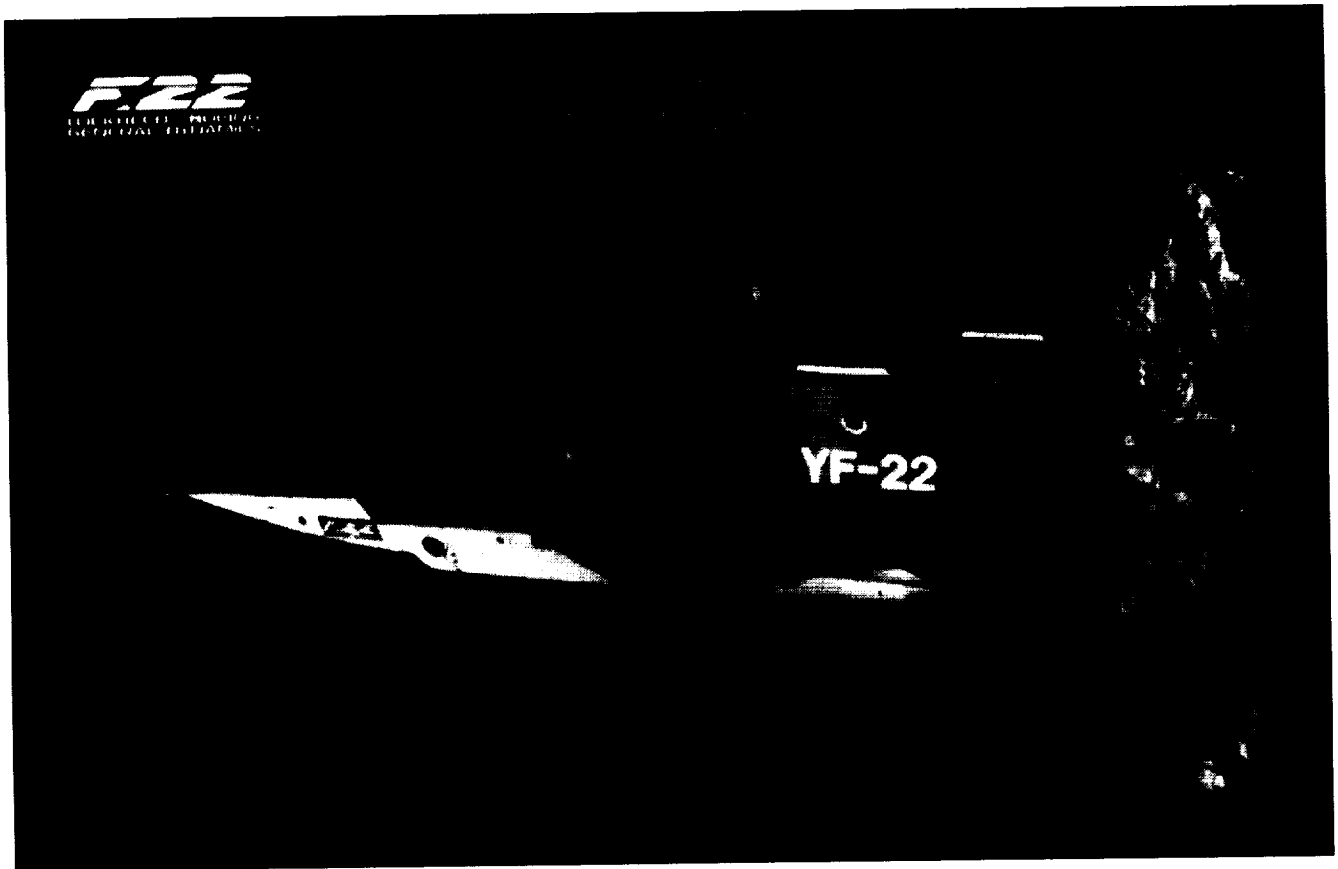


Figure 19. The F-22 balanced and achievable design.

I would like to make one last remark. When I was working for Dick Whitcomb at NASA, there was hardly a week that went by that some industry person did not come in to see him. It was a time when NASA was constantly being asked for technical advice, and Dick always gave that advice freely. He was always there when industry wanted him to help out. This is the kind of cooperation that makes industry want to work with NASA. As a result of that sharing, we have seen the influence of supercritical technology go to just about every corner of our industry. I'm very proud to have worked for him, to have been a part of NASA, and also to be a part of applying that supercritical technology to the F-22 today.

Thank you very much.

Audience: Could you speak to the effect of where the program would have been had it not been for the dem/val program?

Blackwell: I am a strong believer in competitive dem/val programs. First, I believe that it is out of a competitive dem/val that you get the best airplane. Northrop against Lockheed—we produced two fine airplanes. It was a competition down to the last minute. The dem/val program kept the competitive juices flowing like you would never believe, causing each company to stretch to the limits.

Second, without a dem/val program, we would not have a refined set of aircraft specifications that we know are achievable. Further, we would not have identified all the technology risks and brought them to a low level through design and test. Lastly, we would not have achieved a producible, balanced aircraft design and demonstrated its performance. In summary, a dem/val program is a must so you can sort out what you want to build in EMD. In EMD, I want to spend my time not inventing a design but implementing and building a design. Today's aircraft are too complicated and costly to invent and build at the same time.

INTRODUCTION OF ED SALTZMAN

Ken Hodge

Last item on the agenda is the Wrap Up and we're turning to our own Ed Saltzman for that.

Ed is currently a senior aerodynamicist with PRC staff here at Dryden. He's had a noteworthy career as an aerodynamicist for over 40 years with NACA and NASA; although he retired from Dryden in 1981 he's continued to work here part-time for one of our engineering support service contractors as I previously mentioned. His career has been spent conducting aerodynamic research as it affects the performance of vehicles - aircraft and ground vehicles. Some of you may know that in the mid-1970's and early 1980's Ed worked on truck and van aerodynamics in the era of the first energy crisis.

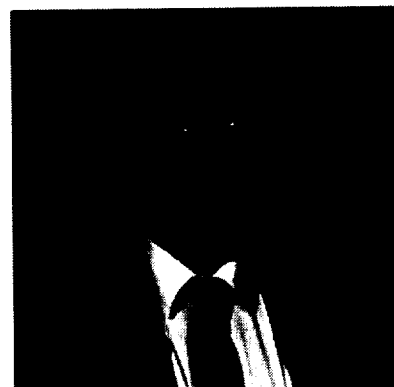
SUPERCritical WING WRAP-UP

Edwin Saltzman

Most of us present today are, or have been, associates of the NASA Dryden Flight Research Facility. Today we honor and dedicate the F-8 Supercritical Wing Research Airplane, a significant transonic research facility.

How do Dryden and transonic relate? Is there a link? We will go on to explore whether there is a link, but now we will establish our purpose in this wrap up, as follows:

- To recognize the man, Dr. Hugh L. Dryden, and his namesake, the NASA Dryden Flight Research Facility, for contributions to experimental transonic aerodynamics research
- To recognize Dr. Richard T. Whitcomb, the inventor of the supercritical wing concept, and his dominance in experimental transonic aerodynamics for more than three decades
- To proclaim that transonic research is not to be relegated to history (in spite of its brilliant history), but to acknowledge that transonic problems still confront us
- To recognize the people who worked on the supercritical wing research airplane that was dedicated today, and to recognize significant members of the wind-tunnel model research team.



With regard to a relationship between Dryden and transonic, we must first define the term *transonic*. Figure 1 shows the range and sources of aerodynamic knowledge as of 1947.¹ Notice the gap in the horizontal bar representing theory. The breadth of that gap was, arguably, a good definition of the transonic region—that is, the speed range in which concurrent supersonic, sonic, and subsonic flow existed over the wetted surfaces of a configuration.

In 1947, the gap in aerodynamic knowledge from wind tunnels was relatively narrow (between 0.10 and 0.15 of a Mach unit), but this gap occurred at a very crucial region. Work was underway toward the development of the slotted-throat tunnel that was intended to help close the gap; but that effort would not bear fruit for another three years.

Three of the data sources shown in figure 1 provided results through the speed of sound. Each of these sources, however, provided only qualitative data because of limitations in instrument accuracy, control of variables, or primitive telemetry equipment.

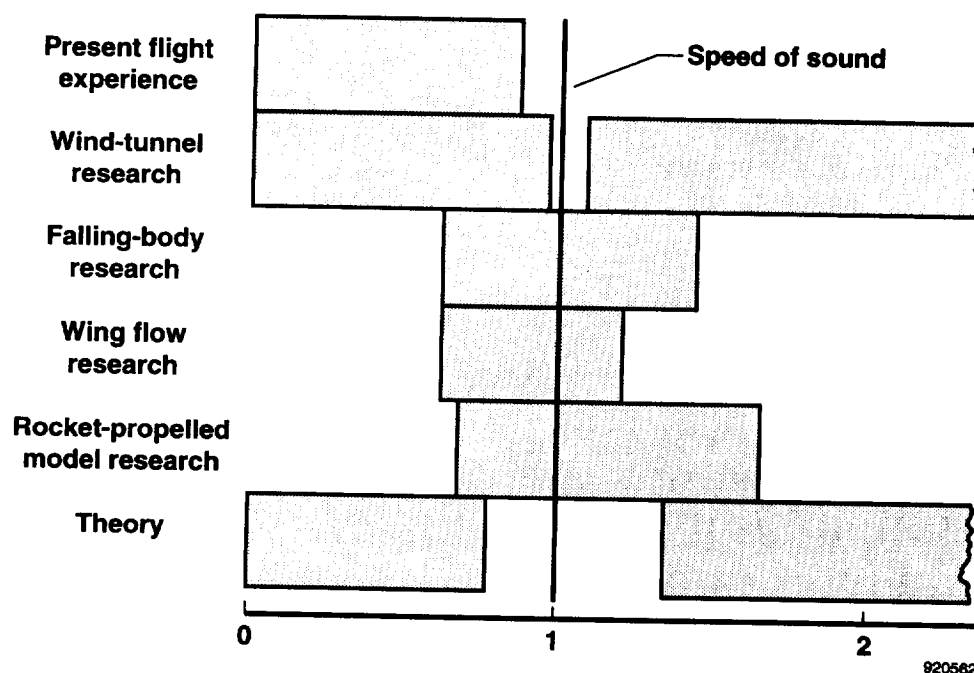


Figure 1. The range and sources of aerodynamic knowledge as of 1947 (ref. 1).

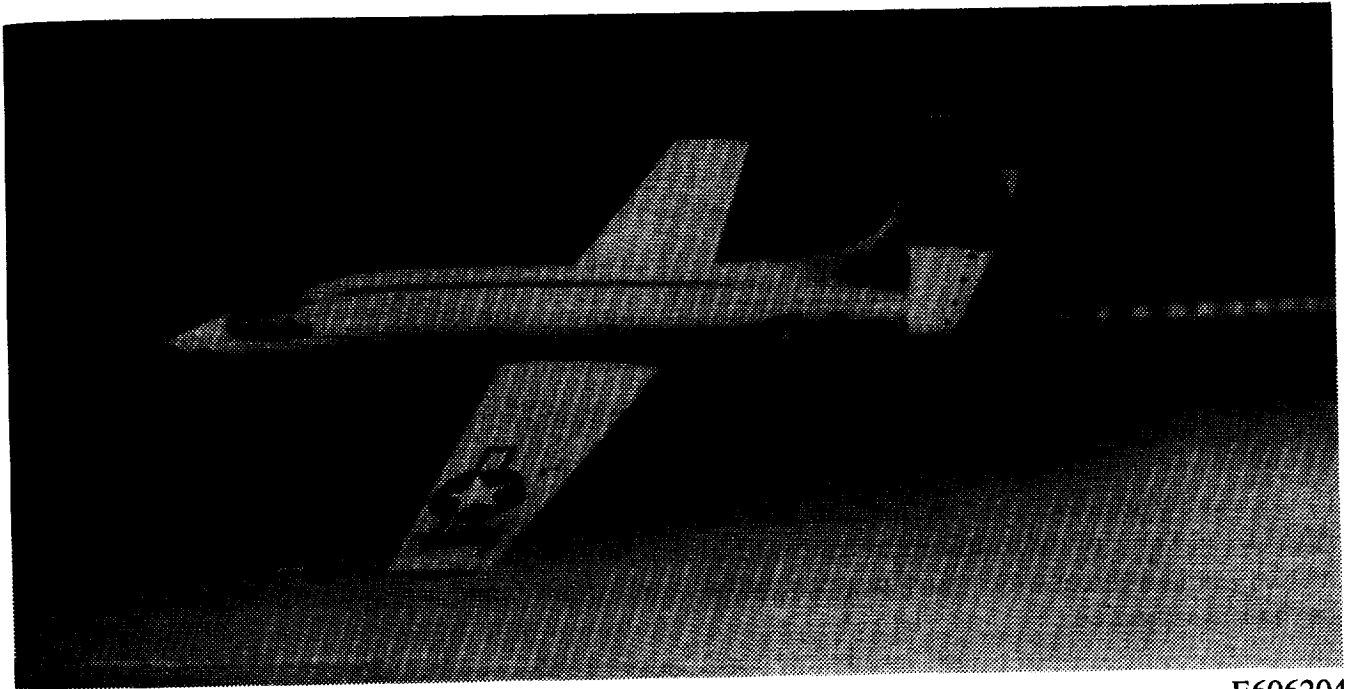
As can be seen from the top horizontal bar in figure 1, information from flight was limited to about Mach 0.85. Some of the people most interested in understanding transonic flow concluded that even if the pending slotted-throat wind tunnel was successful, actual flight experience closer to the speed of sound (or beyond) was needed.

DRYDEN-THE-PLACE AND TRANSONIC RESEARCH

The Army Air Corps, the Navy, the National Advisory Committee for Aeronautics (NACA), and others believed that a special, carefully instrumented research airplane was needed to obtain quantitative transonic data and thereby extend the range of knowledge through the speed of sound. The Army Air Corps, Bell Aircraft Company, and NACA in 1944 began planning the development of the XS-1 rocket-propelled research aircraft (fig. 2).² Approximately three years later, on October 14, 1947, the XS-1 (to be known as the X-1 no. 1) became the first manned airplane to exceed the speed of sound.³ This first supersonic flight reached $M = 1.06$, and this same airplane eventually attained $M = 1.45$. Though most people think of the X-1 in terms of supersonic flight, the airplane was actually a transonic research facility, designed and built to fill in the aerodynamic knowledge gap through the transonic region.

The X-1 was the first bona fide transonic research airplane, and the team that conducted the flight research was the NACA Muroc Flight Test Unit led by Walter C. Williams.³ This organization has evolved into the present NASA Dryden Flight Research Facility. (At the time the F-8 Supercritical Wing research was underway, it was known as the Dryden Flight Research Center). Thus, we see an early link between transonic flight research and Dryden-the-place.

The X-1 airplanes (numbers 1 and 2) in flying through the transonic drag-rise provided valuable wing pressure distribution data, stability data, and control and loads data.⁴ Figure 3 shows the transonic drag-rise, which was first documented in flight from the X-1 airplanes. This rapid increase in drag is characteristic of the transonic region for all aircraft that can attain such speeds. The transonic drag-rise may be thought of as a toll gate. To pass on to higher velocities, a toll must be paid: either an investment for more thrust or fuel, or an investment in research to achieve less drag.



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Figure 2. The X-1 no. 1 research airplane in powered flight (notice shock diamond pattern in exhaust).

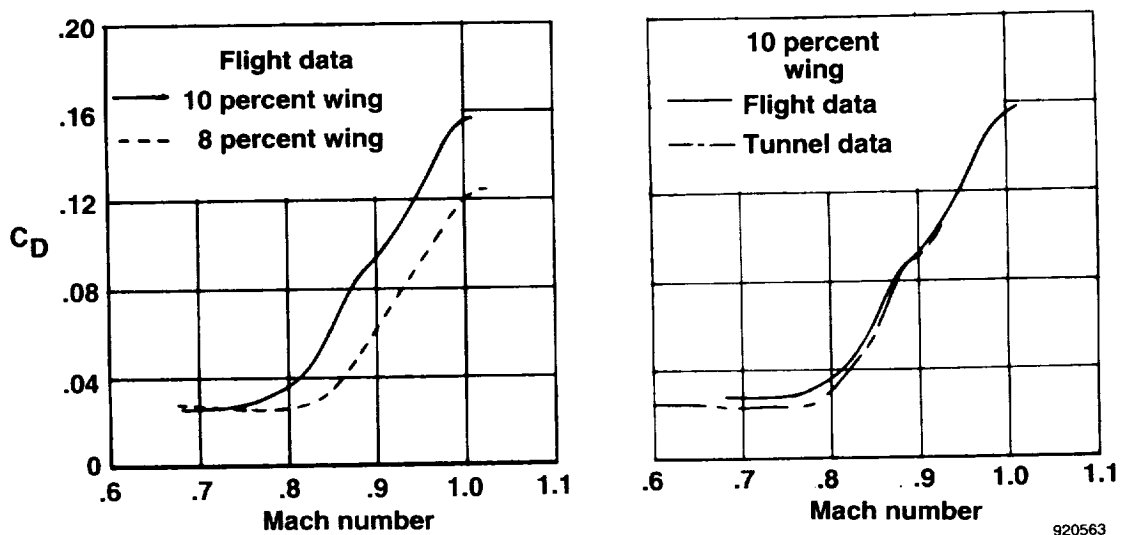


Figure 3. Variation of X-1 aircraft drag coefficient with Mach number, $C_L = 0.4$.

DRYDEN-THE-MAN AND TRANSONIC RESEARCH

Much earlier, during the 1920's, the young Dr. Hugh L. Dryden and two coworkers obtained ground facility data that first showed the beginnings of the transonic drag-rise for airfoils. At that time, most airplanes flew at speeds of 100 mph or less. The absolute speed record was 278.5 mph.⁵

Dryden and his coworkers, L.J. Briggs and G.F. Hull, evaluated the lift and drag characteristics of airfoils ranging in thickness from 10 to 20 percent of chord. They were interested in the effects of compressibility on these airfoils, because the propeller tip speeds on the most powerful aircraft engines were beginning to experience the effects of local shocks.

Transonic wind tunnels were not available in the 1920's, so they borrowed a 5000-horsepower compressor from the General Electric Company.^{6,7} The compressor supplied about 2 atmospheres of pressure to a 30-ft long (by 30-in. diameter) tank. The high-pressure air was discharged from the tank through a 12-in. opening which provided speeds of about 0.95 of sonic speed.

The results of their work are shown in figure 4 in the form of drag coefficient as a function of velocity ratio (Mach number) for two of the six airfoils they tested. Figure 4 is a reproduction of original data plots from reference 7. The two airfoils shown were 10- and 14-percent thick, respectively. The two-dimensional airfoils were mounted outside of the discharge opening, of course, so the experiment was free of shock reflected wall effects; and relatively conclusive data were obtained in spite of the primitive nature of the equipment. At velocity ratios of 0.75 and above (notice that they didn't call this velocity ratio "Mach number" at that early time in aeronautics history), clearly the transonic drag-rise has started, especially for the

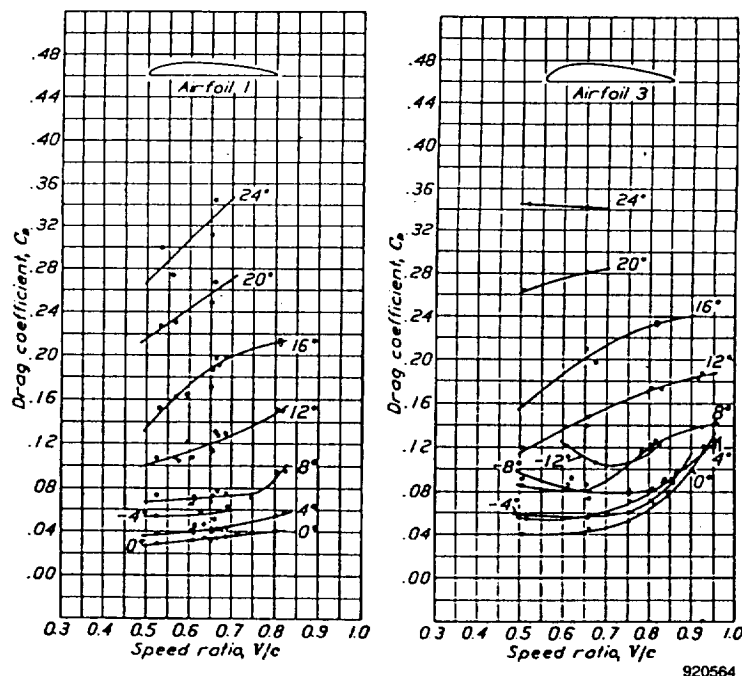


Figure 4. Airfoil drag data showing effects of exceeding critical speed (ref. 7).

thicker airfoil. These results were the very first documentation of the rise in transonic drag for airfoils.* Through this experiment we can establish a significant link between Dryden-the-man and very early transonic aerodynamics research.

Two years after the experiment with the General Electric compressor, L.J. Briggs and H.L. Dryden cooperated again in another landmark transonic experiment. This time they wanted to measure the detailed distribution of pressure over the same airfoil shapes as they had worked with earlier. Furthermore, they wanted to obtain velocities in excess of sonic speed, so they again needed a large compressor. Such a compressor was made available to them through the courtesy of the Chemical Warfare Service.⁸

This borrowed compressor was able to supply an airstream of up to 1250 ft/sec through a 2-in. convergent-divergent nozzle (a simple orifice was used at lower speeds). With this equipment (fig. 5 shows a *crude* reproduction), they were able to expose airfoils of 1-in. chord to velocities from 0.5, 0.65, 0.8, 0.95, and 1.08 times the speed of sound. The highest velocity ratio represents the first supersonic aerodynamic data obtained from a ground test facility in the US—and the year was 1926. An interesting note is that the first ground facility tests in the US to exceed sonic velocity, $V/C = 1.08$, were close in Mach number to the first manned flight to exceed the speed of sound, $M = 1.06$. In addition, the problem of critical propeller-tip velocities and the novel use of borrowed, primitive equipment, combined with innovation by Briggs and Dryden, brought forth two landmark transonic research experiments in the 1920's, a time when most Americans did not yet own an automobile and Calvin Coolidge was president. Thus the link between Dryden-the-man and transonic research was solidified.

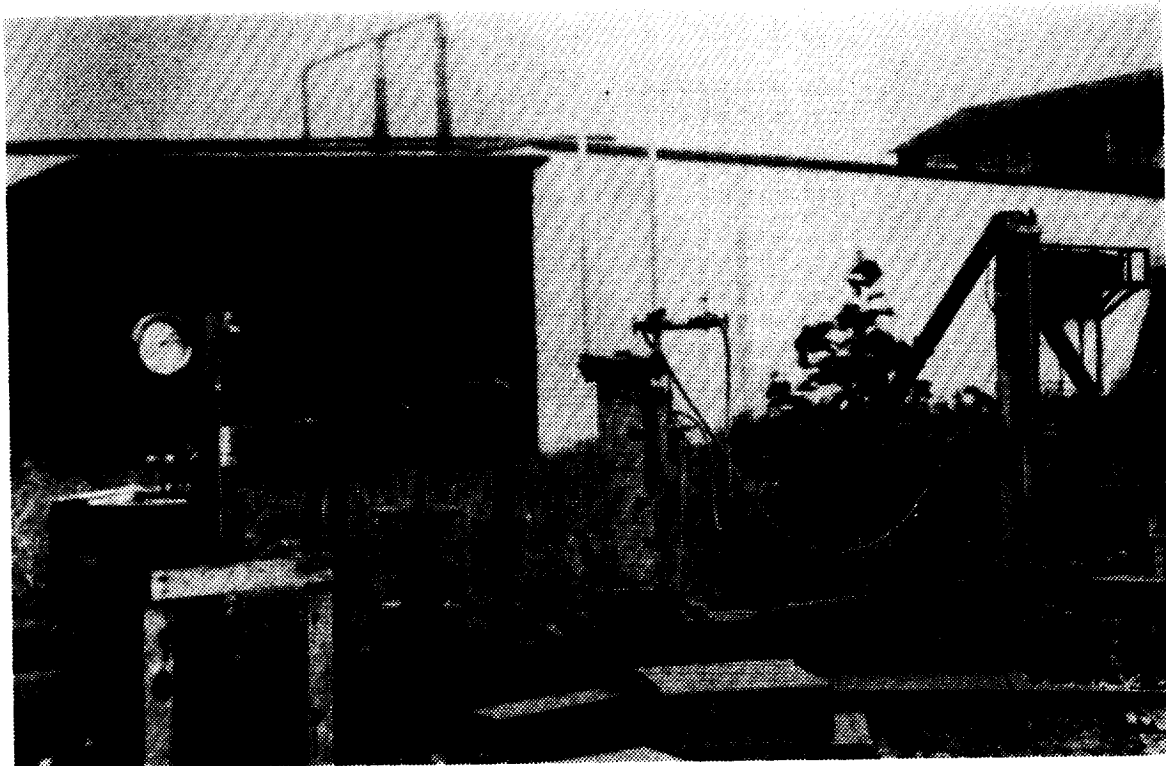


Figure 5. General view of apparatus used to obtain first supersonic aerodynamic data from a ground test facility in the US. Gauges for speed measurement and control valves at the left, airfoil mounting in the center, and gauge for pressure distribution at the right (reprinted from ref. 8).

A LOGICAL SPELLER

Even though transonic data were being obtained during the 1920's, there was no such word as yet. Dryden was well aware that such a word was needed, and he proceeded to invent the word *transsonic*. He had a very logical reason for the way he spelled it. His reasoning was analogous with how one combines the prefix, *trans*, with another complete word to form the new word *transcontinental* or *transoceanic*. Thus he combined the prefix *trans* with *sonic* to obtain *transsonic*.

Because Dr. Dryden was held in high regard throughout the aeronautical community, the engineers at NACA began using his new word. Evidence of this use can be seen* in excerpts from John Stack's Wright Brothers Lecture,⁹ first presented in December 1944 (fig. 6). The first two examples (encircled in fig. 6) are from the text of Stack's lecture, and the third example is from Hugh Dryden's commentary, which was published with the written version of the lecture.

...g, which
city supersonic flow,
support that could be mu.
ar the speed of sound for aero.
o and, finally, any flight at supe... and, except for ...
a passage through the transsonic re... Guidonia which starts
or supersonic research was not igne... been interrupted by destr.
the planning of the N.A.C.A. 1... Guidonia and confiscation of n
tunnel two throat arrangements... ie Germans. Most of the A.
subsonic studies and one for sup... has been directed from t^h
ement was replaced in 19... of transsonic flow. ...steadiness of flow.
ing the same motive... as the result of a deli'... burble' applied to this pi.
high-son... n of, first, the fact... an earlier report is truly
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...arily concerned with compressi
...t with flow separation. I belie
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Figure 6. Transonic or transsonic? Excerpt from Eighth Wright Brothers Lecture (ref. 9).

Three years later Dr. Dryden and Professor Theodore von Kármán were traveling together by train between Aberdeen, Maryland and Washington, DC. They had worked together and had numerous interests in common; consequently they were discussing the need for an official word to describe this critical speed region in aerodynamics. Dryden explained that he and a few NACA engineers were already using

*In John Becker's *The High-Speed Frontier*,⁶ it is reported that because Dryden and his coworkers were using a borrowed compressor, they had to use it at the convenience of the General Electric Company. Thus they found themselves conducting their experiment on Christmas day of 1923 at General Electric's Lynn, Massachusetts facility. The open jet was very noisy, and as Dryden was to write later, "We walked down the street in Lynn (that evening) discussing the jet and noticed passersby staring at us strangely and shaking their heads. It was some time before we discovered that we'd been shouting at each other at the top of our voices, both temporarily deaf as a result of working with our heads only a few inches from the large jet."

transsonic. Von Karman liked Dryden's word, but he did not approve of the spelling! Von Kármán thereupon proposed his own version—*transonic*.¹⁰

In spite of Dryden's logic about how to spell the new word, we know that it was von Kármán's version that has prevailed. Von Kármán explained it as follows: "Dryden was logical and wanted two s's. I thought it wasn't necessary to always be logical in aeronautics, so I wrote it with one s."¹⁰

In pressing his argument with Dryden, von Kármán even quoted the German poet Goethe, who said, "Some logic is desirable, but to be always logical is horrible."¹¹ Apparently Goethe recognized a nineteenth-century nerd when he saw, or heard, one.

THE LINK ESTABLISHED (IN SUMMARY)

So, considering the period from the early 1920's to the late 1940's, a substantial link was established between Dryden, the man and the place, and transonic aerodynamics research, as noted in the following:

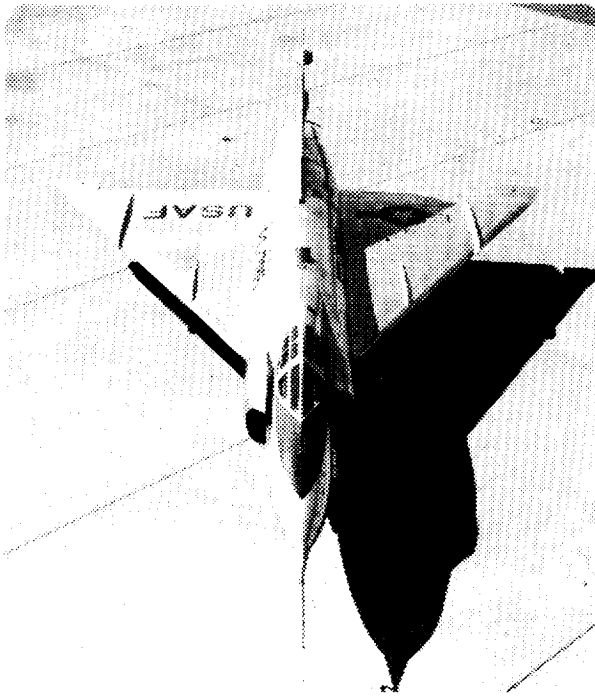
- H. L. Dryden was a key member of the three-member team that generated the first airfoil data demonstrating the transonic drag-rise.
- Dryden was a key member of the two-member team that devised the first convergent-divergent nozzle ground test facility in the US that provided airfoil pressure distribution data through the speed of sound and beyond (to $M = 1.08$).
- Dryden invented the word *transonic*, though his logical mind called for a different spelling.
- By the mid-1940's, Dryden, as a leader, supported, encouraged, and advised on behalf of the X-1 transonic research airplane project; and he saw the effort through to fruition soon after he became the director of research for the NACA.
- The ancestral research organization of the present NASA Dryden Flight Research Facility conducted the world's first quantitative transonic flight research using the X-1 aircraft. At that time, 1946–1949, the facility was known as the NACA Muroc Flight Test Unit, under the direction of Walter C. Williams. As will be revealed in the following section of this wrap up, for the next three decades the flight confirmation of Richard T. Whitcomb's transonic innovations was also achieved at the Dryden facility.

RICHARD T. WHITCOMB AND TRANSONIC RESEARCH

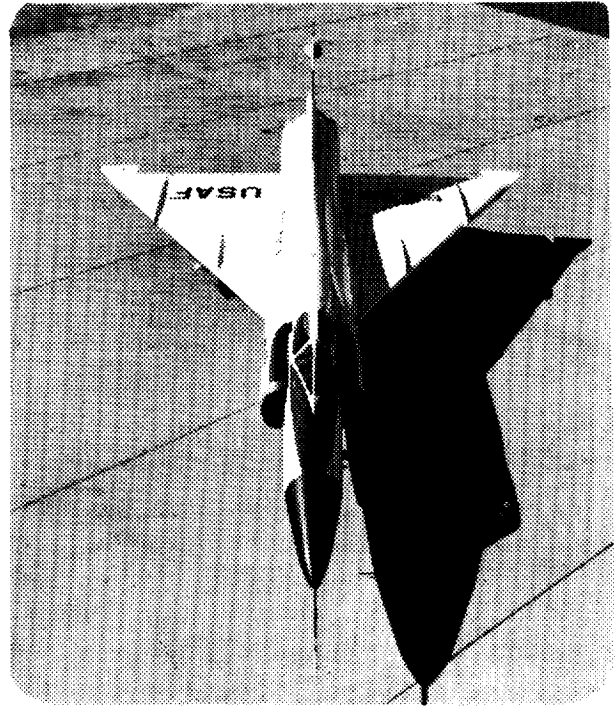
Now, what about Whitcomb (inventor of the supercritical wing concept) and his relationship to transonic research? Did the Whitcomb involvement with transonic aerodynamics extend beyond the supercritical wing?

Hansen's *Engineer in Charge*² indicates that Whitcomb was a member of the team that designed and developed the first slotted-throat transonic tunnel, thus closing the gap in knowledge from wind tunnels that was evident in figure 1. Whitcomb was soon after to invent and conceive of the area rule (fig. 7) during

the early 1950's.^{12,13,14,15} For the F-102A configuration shown in figure 7, the area rule provided a 25-percent reduction in the transonic wave-drag increment.



(a) Prototype airplane



(b) Area-ruled airplane.

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Figure 7. Application of area rule to F-102 airplane, 1954.

During the mid-1960's to the early 1970's Whitcomb invented and developed the supercritical wing concept that culminated in (a) the F-8 Supercritical Wing Research Airplane that was dedicated today, and (b) the associated flight program.^{16,17,18,19} The subject research airplane, figure 8, demonstrated an overall configuration, drag-rise Mach number of 0.965 at the cruise lift coefficient and the drag for the wing did not diverge until $M = 0.98$ to 0.99. This was, and remains, a remarkable achievement.

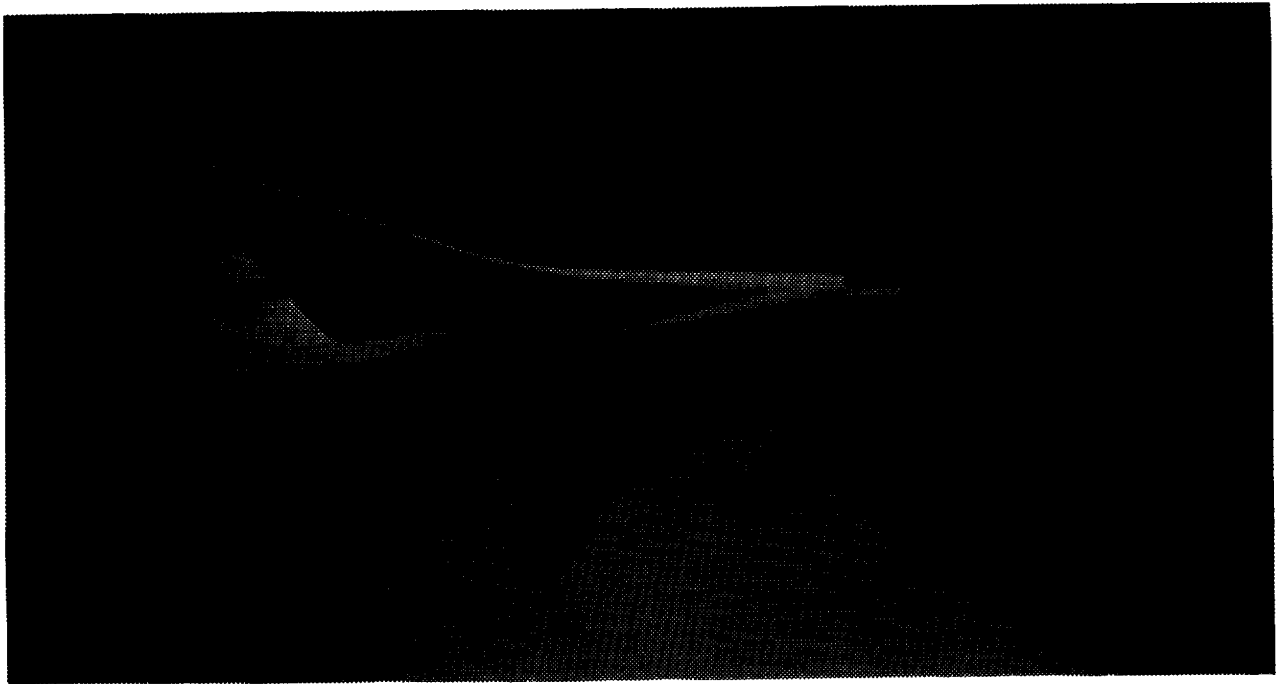


Figure 8. The F-8 Supercritical Wing Research Airplane.

In 1976 Whitcomb published his initial findings on the winglet concept.²⁰ Though applicable at subsonic speeds, this invention held promise for faster transport-type aircraft that would exploit the lower portions of the transonic realm. The flight demonstration of the concept on the KC-135 airplane, figure 9, showed a 6-percent saving in fuel.²¹ For the newer generation of civil transports having higher tip loading, the fuel savings are expected to be even greater.

Each of the inventions or concepts brought forth and developed by Dr. Whitcomb is a landmark transonic technology achievement by itself. Taken together they have had a monumental impact on current high-performance transonic aircraft (and supersonic aircraft), and it is fair to acknowledge that these developments have changed the shape of air vehicles forever.

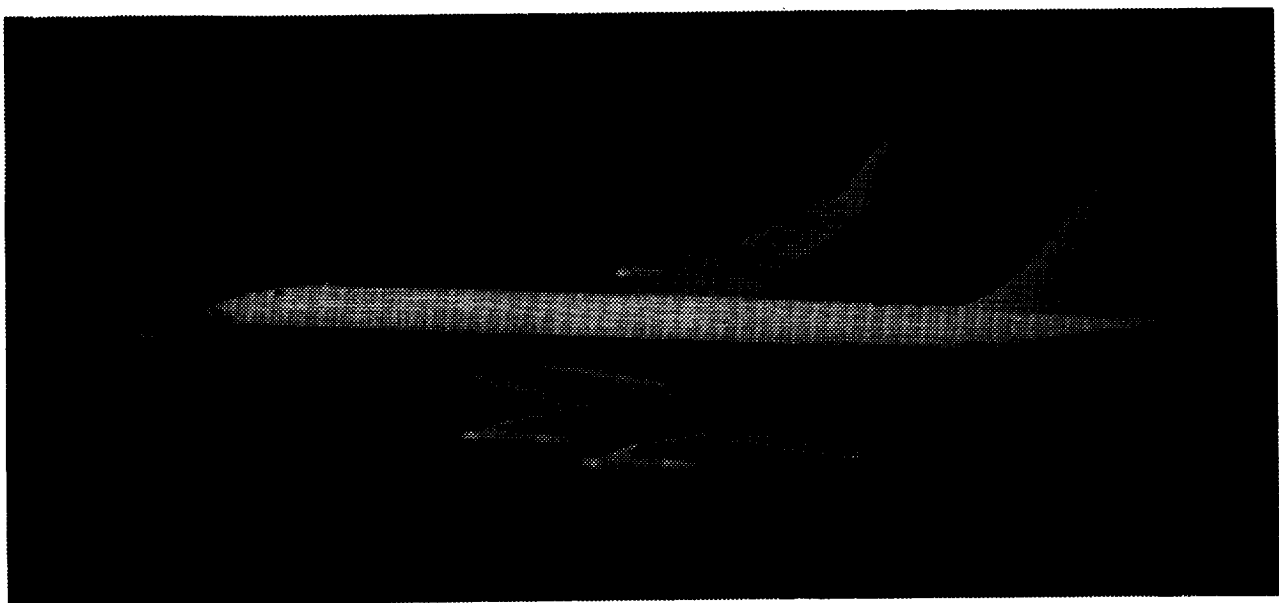


Figure 9. The KC-135 Winglet Research Airplane.

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THE RESEARCH CLIMATE

It is reasonable to ask what kind of agency or organization can spawn and nurture such innovative, profound, and enduring research. Though adequate funding for equipment and personnel is important, this observer believes that it is more important that the organization tolerate, even encourage, a pattern of routine challenge toward conventional wisdom. Conventional wisdom is usually granted a position of respect within our culture. Thus it has its place, but that place is at or near the starting place for technical investigations. A long-standing reliance on conventional wisdom leaves the investigator too close to the starting place and enhances the status quo.

Therefore, it was encouraging to see a statement from a recent address to the American Institute for Aeronautics and Astronautics (AIAA) that said, "In the New NASA we'll welcome a diversity of views and ideas—from both inside and outside the organization."²²

Perhaps NASA's retired deputy administrator had a similar thought in mind when he wrote, "I think sometimes NASA could use a little more internal controversy."²³

It is probably a natural assumption that caution about conventional wisdom is limited to the technical community—primarily the research portion of the technical community. This is not the case, as can be seen from the following paraphrased statement from a 20th-century theologian: If you and I agree on every matter, one of us has ceased thinking.

And perhaps Dr. J.B. Harvey has said it as well as anyone: "... the mismanagement of agreement, not the inability to manage conflict, is the single most pressing issue of most modern organizations."²⁴

It is reasonable to ask whether the spirit conveyed by these four individuals, seemingly expressing concern about reliance upon conventional wisdom, represents the kind of environment that surrounded Whitcomb and his coworkers during the three decades that he dominated transonic aerodynamics research. Did Whitcomb's revolutionary ideas thrive because he worked in an environment unencumbered by conventional wisdom?

No, plenty of conventional wisdom was around—enough to challenge each of his historic transonic innovations:

- Although a revolutionary breakthrough for reducing the transonic wave drag was needed, there were a few in the aerodynamics community who believed and proclaimed that the benefits from the area rule were primarily fineness-ratio effects.
- Conventional wisdom adherents claimed that the benefits from reduced shock strength (provided by the supercritical airfoil) would likely be overshadowed by high-trim drag inherent in nose-down pitching moment caused by loading in the cusp region of the airfoil.
- Other believers in conventional wisdom thought that the winglets were simply performing as extra aspect ratio in disguise.

However, each of these three planks in the platform of conventional wisdom was to be proved false. Whitcomb and his research team had the innovative spirit and technical ability required to overcome conventional wisdom. The original wind-tunnel research performed at the Langley Research Center, the flight confirmation work performed at (what is now) the Dryden Flight Research Facility, and the numerous

commercial and military applications of these three technology innovations have discredited the challenge of conventional wisdom.** We may think of this three-decade struggle to improve the performance and efficiency of transonic aircraft as a contest where the final score was: Innovative, radical transonic research, 3; Conventional wisdom, 0.

Aeronautics researchers and planners of aeronautics programs should remember this score as their work addresses future configurations (whether transonic, supersonic, or hypersonic). Yes, all three of these speed regions represent configurations that must encounter or pass through the transonic "toll gate." As Dr. Whitcomb's research has shown, the magnitude of the toll can be reduced by innovative experimental effort.

After the accomplishments of the Whitcomb team had been confirmed in flight and applied on aircraft throughout the world, the adherents to conventional wisdom acknowledged the benefits of Whitcomb's transonic research for the previous three decades. But now they are tempted to consider the problems of transonic aerodynamics to be solved.

However, at least two of the high-performance US aircraft that flew in the recent Gulf War, and the X-29A forward-swept wing research airplane, display an erosion of transonic aerodynamic design finesse (a slippage of the very specific aero-design principles conceived by Dr. Whitcomb) relative to the aircraft built in the 1950's and 1960's. The specific deficiencies of these three aircraft are that wave drag and parasite drag are too high. These deficiencies are evidence that conventional wisdom learns reluctantly, if at all, and (like childhood diseases) it seems to infect each generation.

Therefore, just because this F-8 research aircraft symposium has retired the original supercritical wing airplane as a research artifact (and just because transonic research, per se, has a history), we should not assign transonic problems to history. The brilliant transonic research findings of the 1950's through the 1970's did not revoke the laws of physics governing transonic flow for future aircraft.

The supercritical wing research airplane that has been dedicated at this symposium will, of course, represent and honor the innovative research of the past. However, it must also remind us that if we limit transonic research to the status of history, the charges at the transonic "toll gate" will be unnecessarily high for some future transonic, supersonic, and hypersonic configurations. It is appropriate to recall the words of Hugh L. Dryden, "The most important tool in aeronautical research, even more important than the large wind tunnel, is the human mind."²⁵

RECOGNITION

One of the purposes of this wrap up presentation is to recognize the members of the research team. At the NASA Langley Research Center the primary members of the research team were Richard T. Whitcomb, Thomas C. Kelley, Charles D. Harris, Dennis W. Bartlett, James A. Blackwell, Perry W. Hanson, and Laurence K. Loftin, Jr. (technical/administrative).

Theodore G. Ayers, though not a part of the Langley team assigned to the F-8 configuration, was then a part of their supercritical wing research for fighter aircraft applications. His subsequent transfer to the

** As was mentioned earlier, there is a legitimate place and function for conventional wisdom. It was proper for conventional wisdom to challenge these three innovations. Unencumbered by nontechnical factors the worthy innovation or concept will prevail.

Dryden facility strengthened the transonic-supercritical capability for flight research. Dryden Flight Research Center personnel involved with the F-8 Supercritical Wing research effort are listed in figure 10.

Larry W. Abbott	Daniel C. Garrabrant	Weneth D. Painter
William H. Andrews	Donald H. Gatlin	Gordon A. Payne
Charles H. Bailey	Gene A. Kenner	Harvey B. Price
Richard D. Banner	Maurice King	Jon S. Pyle
Frank Caroddo	Gary Krier	Walter P. Redman
John P. Cary	Wilton P. Lock, Jr.	Edward J. Sabo
Frank W. Cazier	James F. Maher	Edwin J. Saltzman
Clarence E. Cook	Neil W. Matheny	George J. Sitterle
V. Michael DeAngelis	Leon S. McDaniel	Darrell G. Sperry
Paschal H. Dorr	Frank C. McDonald	Louis L. Steers
James A. Duffield	Elsie B. McGowan	Harold J. Walker
Harold W. Everhart	Thomas C. McMurtry	Lannie D. Webb
Francis J. Fedor	John G. McTigue	Al White
Richard R. Fischer	Lawrence C. Montoya	James Wilson
De E. Beeler, technical/administrative		Donald D. Yount

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Figure 10. Members of the F-8 Supercritical Wing Flight Team.

PERSPECTIVE

It is probably quite normal for a worker to wonder how his or her specialty or subspecialty fits into the fabric of the overall "big picture." We each desire an enlightened evaluation of our contribution, not limited by the time frame and immediate objectives of the particular project. We seek an assessment that has reliable perspective.***

Thus, today's innovators in the fields of electricity and electronics might welcome an assessment of their work, or a perspective commentary (if it were possible), by pioneers in their field such as Tesla, Marconi, or Edison. Likewise, in the field of rocketry, today's worker might desire perspective commentary from the pioneers of modern rocketry—Goddard and von Braun.

In a narrower sense, the same can be said for those who worked on the development and investigation of the supercritical wing concept (those mentioned in the Recognition section or listed in fig. 10). Whether a pilot, planner, supervisor, mechanic, technician, engineer, or some other specialist—an acknowledgment of having been needed (recognition with perspective) is welcomed. And the pioneer for this group would be Dr. H.L. Dryden.

*** perspective (per-spek'tiv) n ... 3. the relationship or proportion of the parts of a whole, regarded from a particular standpoint or point in time. 4. A proper evaluation with proportional importance given to the component parts. [From Webster's New World Dictionary of the American Language].

Dr. Dryden died in 1965, the same year that the first technical report was written on the supercritical airfoil concept. Though he would not witness the final outcome, we know that he was enthusiastic in his support of the innovative transonic research efforts of Dr. Whitcomb.

The team members (participants) who worked on the supercritical wing have a special relationship with the young Dryden. This participant is confident that the young Dryden, who studied transonic aerodynamics with a noisy, borrowed compressor on Christmas day in 1923, would have been excited had he realized the ultimate reach and significance of his first efforts. Those efforts clearly extend to the later work represented by the airplane that has been dedicated at this symposium. A reasonable expectation is that the young Dryden would have considered the work of each team member mentioned herein to be a logical and worthy extension of the transonic experiments that he began in the early 1920's.

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SYMPOSIUM WRAP UP

Kenneth J. Szalai

It's been a fun day for me and I'm sure a fun day for you as well. It's great to see friends and team members alike.

One of the things that stands out here today is the amazing history of the LTV F-8 aircraft as a NASA research vehicle. The second thing is the eloquence of this lineup of speakers that we had today starting with Duane McRuer, Dwain Deets, Gary Hartmann, Ted Ayers, Richard Whitcomb, Tom McMurtry, James Blackwell, and Ed Saltzman. The enthusiasm and the dedication of the people that made these programs successful is still apparent.

I also would like to thank the people who have really been responsible for making this day happen. It seems that when you stand up here everything happens automatically, but that's because of the work of a number of people. The brilliant minds of Milt Thompson and Nancy Lovato conceived this event, I think they deserve a hand. There were also many people behind the scenes: Don Bacon, Joe D'Agostino, Ken Hodge, Dwain Deets, Ed Saltzman, Lou Steers, Jim Phelps, Stephanie Rudy, Karen Richards, Don Nolan, Dan Viney, Cal Jarvis, Marty Curry, Laurel Mann, Sandy Meske, Cheryl Heathcock, and Monique Sullivan. These people have all done a great deal and let's recognize that as well. I'd also like to thank last night's speaker, Richard Hallion.

Finally, we see the role of flight separating the real from the imagined, and making known the overlooked and unexpected. We see the role of flight in discovery, technology acceleration, maturation, confidence, and validation. We also see the role of flight in process development and risk reduction. This is why we think flight research is a discipline all its own.

I recall Duane McRuer's charge to us all—to be prepared for discovery, to keep our eyes open, and our minds sharp.

Finally, we are honored by the presence of Dr. Whitcomb.

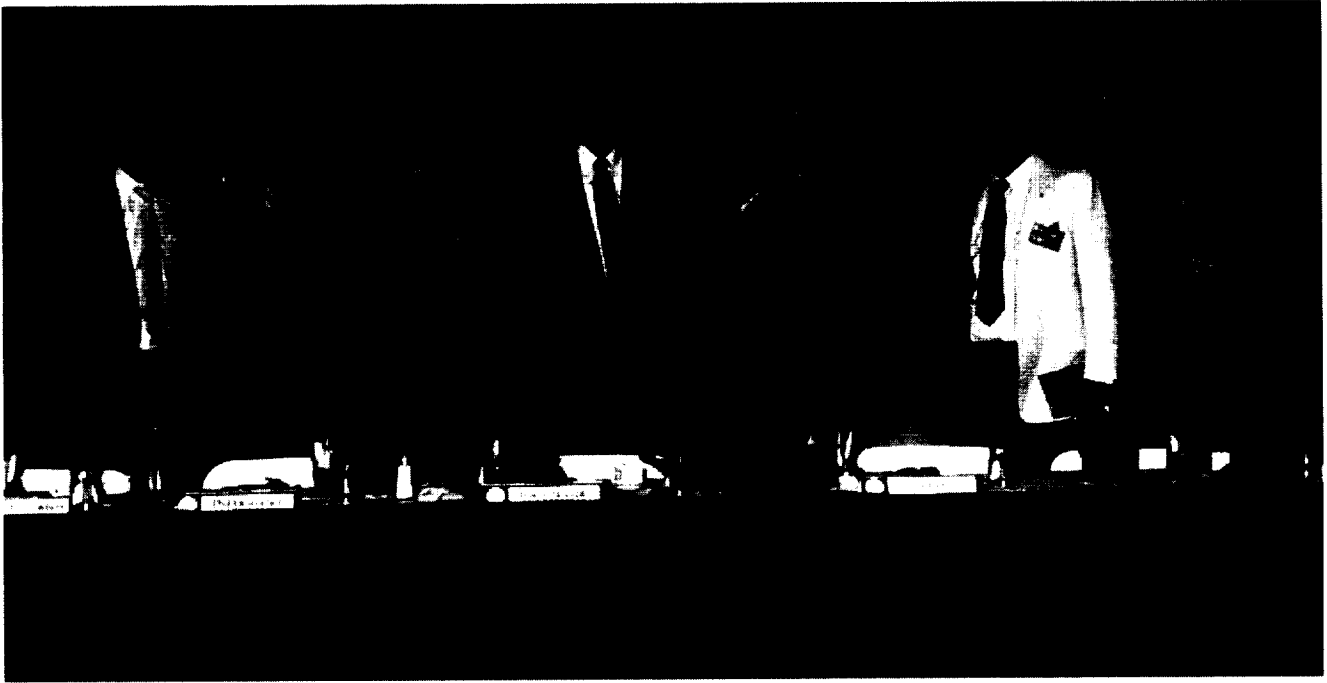
Thank you all for joining in this historic anniversary, God bless you, and drive safely!

**NASA Dryden Flight Research Center
20th Anniversary Celebration of the F-8 DFBW and SCW First Flights**

F-8 PILOTS' PANEL

MAY 27, 1992

**F-8 DIGITAL FLY-BY-WIRE AND F-8 SUPERCRITICAL WING
20TH ANNIVERSARY SYMPOSIUM OF MAY 27, 1992
PILOTS' PANEL**



EC92 05275-23

From left: Einar Enevoldson, Gary Krier, Phil Oestricher, Fitz Fulton, Harry Heimpel, Jim Patton, Don Mallick, and Ron Gerdes.

Ted Ayers: Well, it looks like most people have finished their lunch. I can tell that we have great acoustics in this building. At this point we'll go ahead and start on our lunch program. I would like to say that it appears that Tom McMurtry has maneuvered his way out of another presentation/discussion. He departed this morning with the 747 and orbiter to deliver it east and the latest word we have is they're unable to land because of weather. He may be coming back which would get him here too late to do the other part of his program.

We have commandeered Gary Krier to sit in for Tom and lead this panel discussion. I promised to make short biographical information available on these folks, so let me go through that.

First of all, Gary Krier, who I just said will lead the panel, is a NASA employee. He flew the first flight of the fly-by-wire, also flew the supercritical wing. Einar Enevoldson, sitting next to him is retired NASA; next to him is Phil Oestricher from General Dynamics; Harry Heimpel from the Air Force; Fitz Fulton is retired NASA; Don Mallick, retired NASA; Jim Patton, retired NASA, and promised not to talk about the Mother Center; and Ron Gerdes, retired NASA. We have a tremendous amount of experience represented up here. All of them flew one or the other of these airplanes at some time in their careers.

I might also say that there are a number of other people who also flew the airplanes who were unable to be here today. I would like to acknowledge them by name. Tom McMurtry who I've already mentioned—he was the first pilot to fly the F-8 Supercritical Wing; Bill Dana, John Manke, Ken Mattingly, Rogers

Smith, who gave us the nice fly-by in the F-18; Ed Schneider, Steve Ishmael, Bud Iles, Stu Boyd, and Lee Person were unable to be with us.

With that I'd like to turn it over to Gary who will act as a moderator for this panel discussion.

Gary Krier: I think that the mikes are hot. Is Bill Dana here? I saw him outside, I guess he might come later. If he does come in I'd like him to come up and join us.

I'd like to ask the panel some questions that have been on my mind for a long time. The way I'd like to work it is to ask a couple of questions and get the responses, then have the individual pilots comment about anything on the program they want to; then open it up for questions. If what we say here stimulates a question that you've got to have answered, I'd like to have it, so please stand up and ask the question. The kick-off is this. When we started out with the side stick, there had been a lot of experimental side sticks. Some were force sticks, some were limited displacement, some were total displacement. In the F-16 Program, Phil you finally wound up with a limited displacement stick.

Phil Oestricher: That's correct.

Gary Krier: Can you talk a little bit about how that evolved from when you flew the F-8 and how that translated?

Phil Oestricher: The primary purpose of my flying the F-8 Digital Fly-By-Wire airplane was to evaluate the side stick that had been installed in it. It was identical to the one that we had for the YF-16 Program. I was privileged to come here in October of 1973, a few months before the YF-16 arrived at Edwards to preview the side stick that was in an airplane with which I was familiar. I had been flying the F-8 in the Marine Corps Reserve for about 7 years at that time. This would be a nice way to see just what difference a side stick made. Of course, the flight control system was entirely different, and I think that was more educational than the side stick. At that time we had a completely fixed side stick—well, that's not exactly true, it moved perhaps a tenth of an inch. After all, you do have to stroke the transducers to some extent. To all intents and purposes it was a rigid, fixed stick.

I personally liked that but as we went through the F-16 Program, there were complaints about people who'd done a lot of heavy maneuvering with the airplane, that they were fatigued. I think what these people were doing was putting in maybe 70, 80, 100 lb of stick force when 32 lb would have done the job, which was the max for a high-g command. And, just in the heat of the engagement, or whatever they were doing, they were working way too hard. There was a general feeling that a slight amount of movement in the stick would give you greater precision control. Again, for me that wasn't true. In general, the customer liked it and so we were happy to provide what he wanted. The airplane to this day has a small amount of discernible movement. It's really just enough so that you can feel the stop when you hit it, both laterally and aft. In the forward sense it's still about the way it was in the beginning.

Gary Krier: Thanks. Any comments from the pilots' panel on side sticks? Harry, how about this?

Harry Heimpel: Sure, I was flying with the F-16 test force at the time we took the side stick from the fixed to the small amount of movement. There was a lot of controversy about it. I happen to be from the other school where I got my arm tired a lot so I thought the limited motion was a good idea. The decision that was made—as we make a lot of the decisions in the Air Force—the commander of the Tactical Air Command flew the airplane and decreed that we going to have a motion stick. From an engineering aspect that was very simple. It was just, "How much?"

Gary Krier: Other comments? A supercritical wing question. Anybody that's seen Jim Patton's work on spinning the airplane has got to have great respect for this man's work. Have you ever spun an airplane with supercritical wing? How does it respond?

Jim Patton: I'd like to make a couple of remarks, not about the Mother Center but in another direction. I think it was tremendous and I applauded every time we worked together with different centers. There's a lot to be gained and a lot to be avoided in the inherent competition between centers to get the engineers and the pilots working together. I think that should be exploited to the fullest in every opportunity. I thought that was just great and as it happened with every case in which I participated, I think it has helped all of us.

Gary Krier: Great idea. Don?

Don Mallick: Gary, I'd like to make a comment too. Within the various test pilot offices in NASA there has been a procedure that there's usually one or two primary test pilots on a program. It has to be that way because they're very complex. These people have to really get up to speed, but when the opportunity avails itself, the other pilots are usually allowed to fly one or two qualitative flights in the aircraft. That was my situation with the supercritical wing. Some of what Jim was saying is that it's an excellent educational approach to things. It is still being done today. As I looked out there at that supercritical wing today, and it's been over 20 years, and it's so beautiful. What I remember about it is sitting in the cockpit and getting closed in and it was a little bit tighter than the other F-8 that I had flown—but then also that it was a sweet smooth thing to fly and clean. Even when you're pulling in gs it felt so nice. I would have never had that opportunity, even at the time I was chief pilot, if we didn't have that policy that tried to allow people to be exposed to it.

Gary Krier: That's a great comment. I think that had it not been for that attitude, I never would have had the chance to fly some of the airplanes that I got to fly, and we all got to fly the YF-17 with never a training flight. We did some simulation work and some check-out work with Northrop and then we all went out and flew some test missions. It really worked out well. Ron Gerdes, have you got comments?

Ron Gerdes: My comment has to do with the only flight that I flew on the supercritical wing airplane. I never quite got it back to the chocks like I was supposed to, like I was briefed. We had a utility hydraulic failure which was no big deal. I had to go ahead and we landed out on the lake bed and I guess they weren't quite ready to bring me back in because I landed early. There I was sitting by myself on the lake bed out here. They said, "Don't shut the engine down, don't try to open the canopy." (You had to blow it off I guess to open it). So there I sat sort of dumb, not really happy about it, waiting for the crew to show up. After about 10 minutes I guess they finally met me down there and got me out of that cockpit. That's my most memorable part of the flight.

Gary Krier: Well, how about hearing from my mentor, the guy who took me in when I was the FNG and taught me a lot about test flying, Fitz Fulton.

Fitz Fulton: Mighty nice comments there, Gary. I, like Don, only flew the airplane one time, and I looked back like 20 years to pick out one great spark to say that I really remember exactly what happened. I don't remember that well except that it was a nice flying airplane. The other thing I remember was that it was phenomenal, with a low amount of fuel flow, you could get up to an altitude and you pull it back to cruise and the numbers you looked at on fuel consumption were so much less than most any other fighter I've flown. It was a very good illustration to the man in the cockpit that, "Hey, this really is doing some

good!” Of course, that’s what has transpired now into transport airplanes; everyone gets increased range as a result of the supercritical wing.

Ted Ayers: Excuse me Fitz, if I could ask some of the pilots, if you bump or touch the mikes you’ll cut out. So keep your hands off the mikes, please.

Gary Krier: It’s called an audio PIO, Fitz. That’s a perfect segue into a comment by Einar. Einar’s got some very explicit and some very good technical information on the PIO on the task that he did that you saw on the film. If Einar would explain that, I think we would all be the better for it because I didn’t have the exact correct story.

Einar Enevoldson: I hope I have this straight. John Manke and I were flying a series of tests in support of analysis of the shuttle PIO. The test was to fly the augmented, the SAS on F-8, with various time delays between the pilot’s command and the actual response of the flight control computer. To create as much a sense of urgency, or as we say, to demand the highest bandwidth from the pilot, we gave ourselves the task of landing on the white line on the runway. The idea was to touch down not before but as close beyond that as possible. This was about as good as we could do.

I should paraphrase Russ Barber’s description of PIO testing which has to do with self-infliction of pain. It’s difficult to do. Visualize putting your thumb down and hitting it with a hammer, because it’s very serious, and until you actually do it, you don’t know what the result is going to be. You suspect it’s going to be bad. The only way you can simulate creating a true PIO environment is to have something you’re going to hit if you don’t move the controls. To simulate the shuttle PIO, you have to put an alligator pit at one end of the runway, and solid objects like big redwood trees on the other end. You mustn’t hit either of those! Within the limitations of the task we shot for the white line and worked as hard as we could. I flew that case and we’d done about five or six flights each and we were each flying the same cases. We were up to about 300 msec, 300 to 350 msec, and felt terrible. But neither of us had actually PIO’d the airplane. It’s sort of impossible to fly an airplane artificially. You had to adapt to it as a pilot and do the best you could given the circumstances of the test. So I flew it and I said, “Boy, it’s really awful, John. I think it’s going to PIO.”

John said, “Yeah, I’ll work it a little bit and see if I can give it my best shot at creating a PIO.” But he didn’t actually PIO the case. He landed, nice landing, close to the white line, and then in the course of taking off, he touched the tail skag and that tripped off the SAS and he was now flying an airplane with 300-msec time delay and poor pitch damping. He immediately ran into a reversion PIO which was beautiful footage. The number of cycles you saw was how long it took him, and I don’t know whether he actually reengaged the SAS or disengaged the time delay, but one of those two events he was able to do and immediately was back under control. In retrospect, it probably was not the smartest system design to leave the time delay on and turn off the SAS but we knew that after the fact.

Obviously no one gets very far into fly-by-wire discussions without talking about PIOs and as far as we can see they remain a vital topic. It seems like every new generation of airplane has some control systems designer discover a new way to create them. Have to dig them out each time.

Gary Krier: Well said, thank you. How about comments from the audience. Comments and questions. Yes, Ken.

Ken Szalai: Although I had my eyes closed during the PIO, I wanted to mention that in the testing world there were some things that were done and Gary led this activity to make them as safe as possible. One was the decision to do those tests wing down at high speed as opposed to wing up where it would be close to stall. To do those gear down, we took the gear doors off the airplane to provide gear-down capability at high speed. We also had a time delay cut out on the stick. On the first oscillation which was done in direct, John Manke said "Oh no!" and pushed the time delay off and the next oscillation he said, "This is not damping very much!" and he selected SAS and the next oscillation finally damped. He was calmly going through the mode changes to get out of that. It looked like a short time period but actually worked through it successfully.

Gary Krier: I think it only took him half a life time to make those decisions!

Ken Szalai: Gary doesn't remember but he called on the radio as he turned away from the runway and said, "John, I didn't have data running, could you run that again?"

Gary Krier: And that's why I'm in Washington! Milt, could I ask you to make a couple of comments on the programs overall based on what you've seen over the years? I would appreciate it.

Milt Thompson: What specifically Gary? I mean you caught me off-guard here. I wasn't supposed to talk!

Gary Krier: Well, a couple of things, Milt. What I remember about the airplane and the programs, of course, were all the flying experiences. In addition to that, there were managerial things. The program was run as if we all had an equal stake in it. There was no hierarchy, and no differentiation of duty. There were people who were cross-working all the time. The people who were working the back-up system were talking with the digital people; they had close coordination. As I mentioned earlier, electricians were doing things like sanding airplanes. Can we still run a program that way, where the top person can talk to the bottom person in the way Paul Bikle used to do, and the way that Phil was talking about at General Dynamics? They are trying to promote that kind of a loop now where somebody in the pilots' office can talk to senior management.

Milt Thompson: Yes we still have that. We have to continually remind people that they can come and talk to anybody in the front office. Particularly in my case, you know, that's my whole job to look after the day-to-day flight activities. We encourage people that have a problem or any kind of concern to come and let us know about it. We can't do the job on our own. We aren't smart enough to know the details or the intricacies of every airplane. We have to depend on the people on the projects to be honest about their problems and highlight the problem to us and then we can delve a little deeper into that problem. The only way we can maintain a safety record is to have open communications. I think it's still working very well.

Gary Krier: Thank you Milt. Other comments, please?

Audience: In witnessing the fly-by-wire testing that you folks did, brings to mind the B-2 and F-22 Programs that deal with intricate and complex skill work to do on the software prior to involving flight. They go through a lot of complex testing man-in-the-loop simulators. Can you give us insight as to the type of simulations that were used in the mid to early 1970's and the fly-by-wire and perhaps how that benefitted your flight testing; and what improvements you've seen since then in terms of before flight testing that you see as quantum leaps in that kind of technology?

Gary Krier: Ok, comments on simulation of fly-by-wire. I'd like to start with Phil to make a couple of comments about what was done in General Dynamics in the early days.

Phil Oestricher: Unfortunately, we attempted to save a lot of money on simulation, especially in the display area. We checked but there was no doubt that the simulation was dead accurate. The problem was that the simulation was so primitive that it simply did not bring out the idea that there was roll PIO potential lurking in the airplane. All of the pilots, the six of us on the program at the time, after the big adventure you saw on tape, went back to the simulator and the answers each time were, "Well, I don't see anything there. We know there's a problem, but it just doesn't come through," because the simulation was no good. In my opinion, what has really happened over the years, is that we got very good on very short lag display techniques to where the pilot has a reasonable view of what the world is supposed to be doing and thus the simulation is really useful.

Gary Krier: Fitz, you should have some comments and I'll ask you to extend them from beyond fly-by-wire and supercritical wing to include some of the remotely augmented vehicle things that you have done in the Controlled Impact Demonstration (CID) Program and the value of simulation there.

Fitz Fulton: Well, obviously this is not fly-by-wire, but fly-by-no-wire, I guess. I'm thinking about the crash program that we had on the Boeing 720. Of course, we did that on simulation, but the end of that simulation was the airplane responding to my controls in the ground cockpit. We found it extremely valuable to repeat the profile that we were going to crash the airplane on, we repeated many times because of the safety crew on board the Boeing 720. By having that, you had the confidence that you could go ahead and fly the airplane, bring it around, and touch it down. In our case, we had a real airplane that was on the end of the string and it responded to what I did in the ground cockpit. That's not quite simulation, but it certainly shows the value of practice and doing what you would do in real life. Later on we crashed the airplane not exactly like everybody had planned, but sometimes when you plan a test you can expect disappointing results and prejudice what the results are going to be.

Gary Krier: Thank you. Harry, have you got some comments to make about the fly-by-wire simulation and AFTI simulations?

Harry Heimpel: I'd like to finish Phil's story. General Dynamics went on after the basic F-16 Program and AFTI came along as their next effort. As a result of the experience gained from our partnership with NASA on the F-8 and AFTI Programs, and the experience from the F-8 simulations, General Dynamics committed probably the greatest industrial capital investment in simulation in a center facility of any of our major incorporations—I know Phil had a lot to do with it having had first-hand experience with the lack of that simulation. The first full-dome visual sim that GD did was, of course, for the AFTI which was the full hardware-in-the-loop in terms of all the computer simulation. I don't know how many hundreds of thousands of hours we ran that simulator and simulated, and simulated for the months before we flew. The result was that the airplane flew exactly like the simulator did. I think that in preference of the value of that activity in the fly-by-wire area all of the contractors have that same experience.

Gary Krier: Thank you. Other comments? Ok, I guess I will conclude the Pilots' Panel. Any last remarks from the pilots? Who wants the last words? Fitz?

Fitz Fulton: Well, let me make a comment. I never flew the F-8 Fly-By-Wire, and I retired from NASA 5 years ago. I had never flown a fly-by-wire airplane until about a month ago when I was invited to fly the F-18. That was my first opportunity to fly a fly-by-wire airplane and that was a delightful flying

airplane. It brought home to me the real improvements and the significant changes in flight controls that happened throughout the time I was in the flight testing business. Thanks for letting me fly the F-18!

Gary Krier: This is from a guy that's got bags of time flying at Mach numbers greater than 3. Phil?

Phil Oestricher: I'd like to make a comment of appreciation and a hearty "well done" to the people who worked on the digital F-8. I had probably 600 or 700 hours on the F-8s when I came here to fly the airplane. It was a love-hate sort of thing. I loved the performance, I hated the way the airplane handled. It just was not a good-flying airplane, in my estimation, particularly any time the gear was down and the wings up, it just didn't fly like it ought to. On my second flight in the F-8, I took off on the side stick, which was a new thing for me in the F-8, and I don't think I've ever flown a better airplane for take off or landing. This team did an outstanding job in every aspect of developing that airplane, and I'm talking Phase 1 now, not the later approach to the job. You did a wonderful job on that and believe me it showed that the F-8 was a great airplane held prisoner by its flight control system. Thanks.

Gary Krier: Going, going, gone!

Ted Ayers: Thank you very much folks. Thanks, Gary, for filling in for Tom here (we'll get even with him). I'd like to make a few comments on this and to summarize what we heard here. There are three things that stand out in my mind. One is certainly simulation, simulation, simulation; practice, practice, practice. As Fitz said, no matter how many times you practice, sometimes things don't go quite right at the end. However, you hit the target Fitz, that's what we were after. To practice continually, and even after doing all of that, you still go out to fly and something can and something does somewhere along the way usually occurs that was unexpected. I believe that we learn from all these events. We've seen recently the YF-22 airplane that was involved in the accident here at Edwards. These things serve to bring us back to reality that we chug along and everything works fine and all of a sudden something bites us. You can never relax, you always have to keep in mind that safety is of paramount importance. I believe that Milt in his comments—and by the way Gary, thank you for getting Milt up here, you did something that none of the rest of us have been able to do in this whole two-day event—Milt in his response to the question about safety reiterates the need for openness. That is not always an easy thing to do, particularly when you have large change overs in people. It's important to keep stressing that. I agree with Milt, I think we do have that and our record speaks for itself in this area, but that doesn't mean that we don't have to be careful tomorrow either. The other thing that I believe is important, and Jim Patton touched on it, and it's probably something that isn't done enough, and that is that more people, more pilots in the pilot community flying these airplanes because that spreads the information around, gets that knowledge up to the community at large. It's critical to people understanding the technology that is being developed. We heard in the case of Phil and Harry Heimpel talking about the benefits of flying an airplane like the F-8 when they went on into pre-production and production airplanes trying to prepare themselves for any events that happen there. So the research airplane provides not only the good tool for the researcher, but good information for the pilot community to go out and fly other airplanes from.

The last thing is the ITF, Ken says that wasn't the last thing, but it's the last thing I can remember now, Ken. We are sitting for the first time in the Integrated Test Facility which has been too many years in coming. We've spent a lot of resources on this facility. You happen to be sitting in one of six test bays. We have the capacity to house a lot of airplanes, we can open up the bays on the other side into one large massive bay for big airplanes. This facility has a center spine running down it with control rooms as you can see in the windows up there. It has a computer interface capability, hydraulics, which allows us to have a man-in-the-loop test facility with the airplane right in our simulation. The only thing that's lacking is a

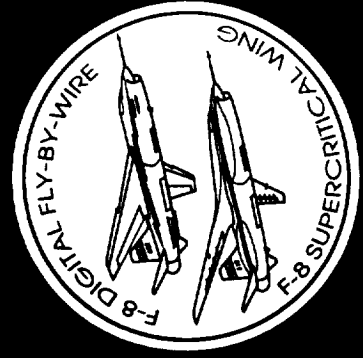
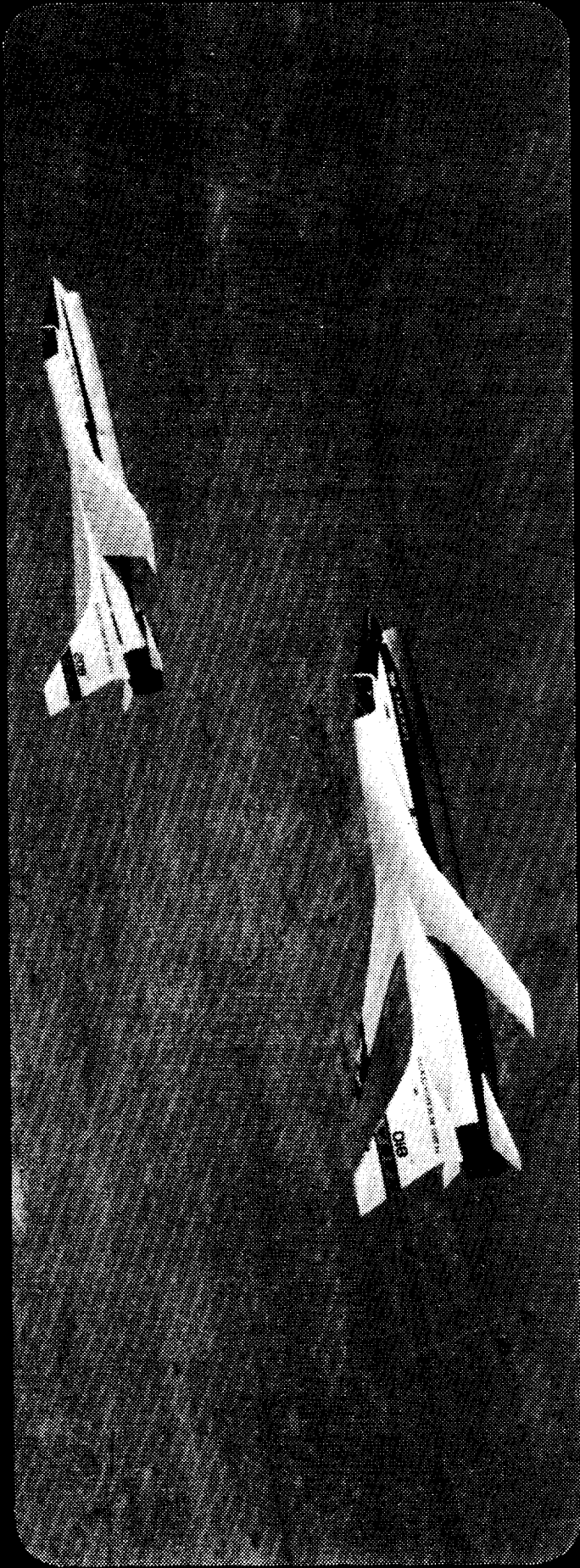
thrust stand to run up the engine on. This whole facility was designed and built to answer some of the questions that you folks were talking about, and that is getting the airplane in the loop and doing the simulation test and retest, for doing verification and validation to make sure that when you do go out to fly in the airplane you do have the highest level of safety that you can get.

A need for this capability is further increased by the airplanes we're flying today like the F-16, the X-31, X-29, or the F-22 which have very high levels of relaxed or negative stability in them where things can happen very fast and it's too late to try and correct after the incident happens. This provides us an extra margin of safety. We're looking forward now to getting all the staff settled in and getting it cranked up and going. This is the first hosted event and it's good to be in here.

Again, let me thank the pilot panel. I don't have all the information, but there's probably close to 100,000 hours of flight time here at the table. With the people who are not here, but who were mentioned, there's probably another 100,000 hours of flight time. You are probably looking at the highest level of flight experience in the country today right here giving you information first hand.

Thank you very much.

20th Anniversary

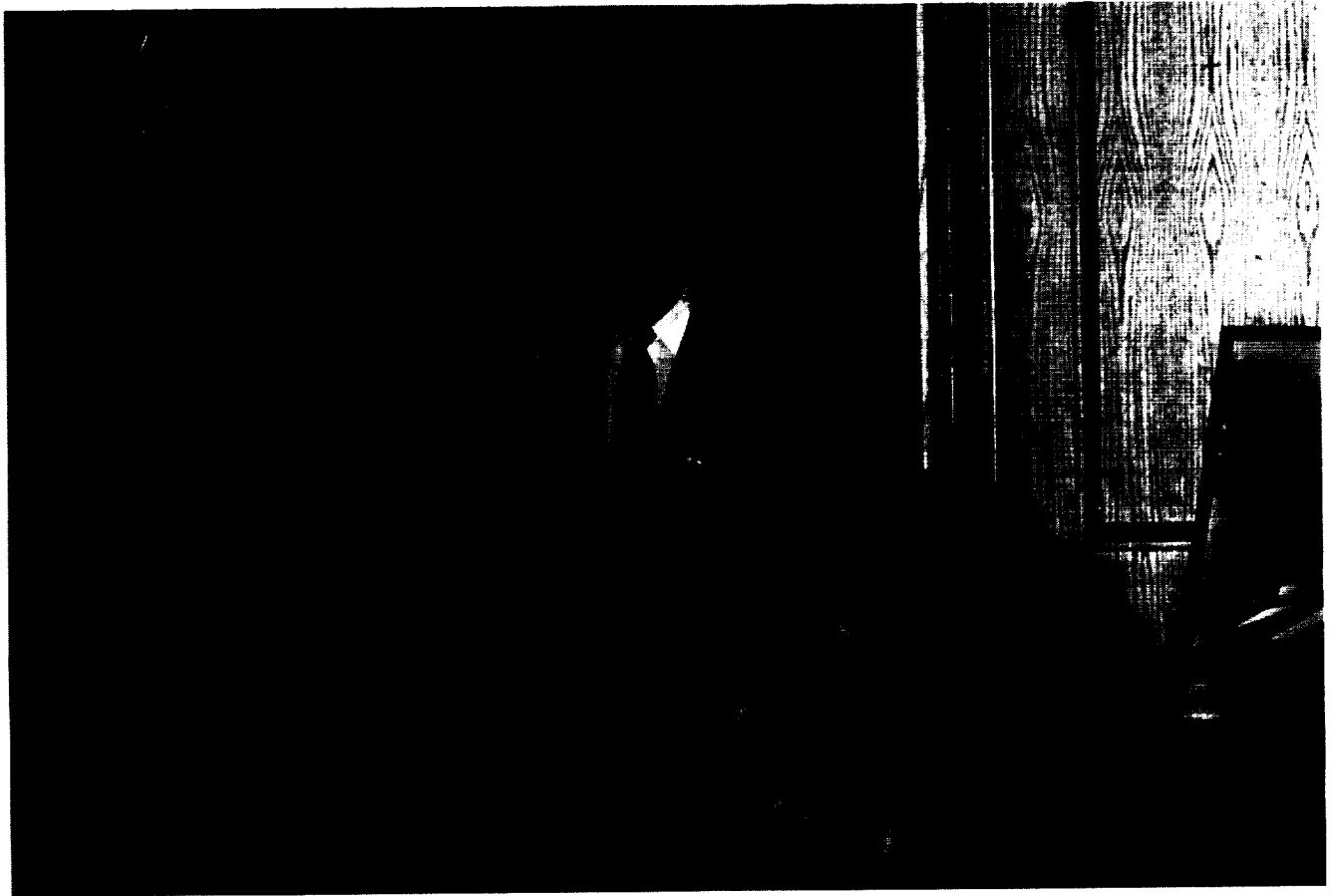


- Dinner at the Desert Inn May 26, 1992 featuring a talk by A.F. Historian Dr. Richard Hallion, "The Gulf Air War: A Survey" (6:30 Social Hour/No Host Bar - 7:30 Dinner - 8:30 Speaker)
- Symposium May 27, 1992 from 8:30 a.m. to 4:00 p.m. in the ISF (Bldg 4825)
 - Dedication of permanent F-8/DFBW and F-8/SCW aircraft displays
 - Lunch with pilot panel discussions in the ITF (Bldg 4840) following dedication
- Check your X-Press for details on lunch and dinner tickets or call Cheryl Heathcock at (805) 258-3449 for more information

Purchase Tickets No Later Than May 18 - They Will Not be Sold at the Door



Obverse and reverse of medallions struck for F-8 DFBW and SCW first flights' 20th anniversary celebration



Guest speaker Dr. Richard P. Hallion

The F-8 Anniversary Celebration included an after-dinner presentation "The Gulf War: A Survey" by noted aviation historian and author Dr. Richard P. Hallion. Although the text of his talk is not available, the excellent supporting slide material is reproduced in this section. In addition to an informative, quantitative summary of the Gulf War, the role of high-technology aerospace systems and space-based C³ in providing air superiority is clearly stated. In the words of then-President George Bush, "Gulf Lesson One is the value of air power!"

THE GULF AIR WAR: A SURVEY

Dr. Richard P. Hallion

Air Force:

750 fighter, bomber, & armed trainers
200 miscellaneous types
160 armed & troop-carrier helicopters
Soviet & European AAMs, ASMs, & PGMs

Army:

Approximately 60 regular divisions
8 Republican Guard divisions
5,700 tanks
5,000 other armored vehicles
5,000 other support vehicles
3,700 artillery pieces (tube & rocket)
Over 800 SCUD & SCUD-derivatives

Air Defense Forces:

16,000 SAMs: 7,000 radar-guided and 9,000 heat seeking
7,000 antiaircraft guns

Figure 1. Iraqi military capabilities.

August 6: King Fahd invites nations to bolster Saudi defenses

August 7: F-15s deploy for Saudi

August 8: F-15s arrive Saudi (15 hrs, 8,000 mi. non stop)

2 CVBGs arrive on station

Troop airlift to Saudi begins

**August 21: SECDEF Cheney proclaims sufficient forces in Saudi
to defend it from Iraq**

Figure 2. Gulf air deployment.

Air Force prepositioned \$1 billion worth of supplies in Gulf in 1980's

- **Fuel and equipment**
- **Ammunition and weapons**
 - **Sufficient smart bombs to destroy 3,000 tanks**
 - **2 million rounds of 30-mm cannon ammunition**
 - **20,000 cluster bombs**
 - **45,000+ MK. 82 - 500 lb bombs**

Figure 3. The value of prepositioning.

- **In first 5 days, airlift moved:**
 - **5 fighter squadrons**
 - **An AWACS contingent**
 - **Brigade of the 82nd Airborne Division**
- **In first 18 weeks, airlift moved:**
 - **Equivalent of 2 1/2 Berlin Airlifts**
 - **200,000 people; 210,000 short tons of cargo**
- **By middle of Desert Shield, 65 aircraft/day delivered 8,000 troops/day to 16 different airfields**
- **By middle of Desert Storm, 127 aircraft were landing each day in Gulf—one every 11 minutes**

Figure 4. The value of airlift.

Operation	MTM/D	Aircraft
World War II "Hump"	0.9	C-46, 47, 54
Berlin Airlift	1.7	C-47, 54, 74, 82, 118
Operation Nickel Grass	4.4	C-141A, C-5A
Operation Desert Shield	17.0	C-141B, C-5A/B

Figure 5. The airlift in historical perspective (millions of ton-miles of cargo flown per day).

- **Desert Shield and Desert Storm required 75% of KC-10s and 44% of KC-135s**
- **Demonstrated the synergy between airlift and tankers**
- **During Desert Shield, tankers:**
 - **Flew 4,967 sorties totaling 20,000 flight hr**
 - **Refueled 14,588 aircraft, including 5,495 USN/USMC aircraft**
 - **Off-loaded 68.2 million gal of fuel**
- **During Desert Storm, tankers:**
 - **Flew 15,434 sorties totaling 60,000 flight hr**
 - **Refueled 45,955 aircraft (20% of which were USN/USMC)**
 - **Off-loaded 110.2 million gal of fuel**

Figure 6. Air refueling support.

- **Began upon outbreak of crisis**
- **Initial concept established by mid-August, 1990**
- **Emphasized a FOCUSED AND INTENSIVE offensive air campaign—no gradual escalation**
- **Three key phases:**
 - **Attacks to inflict STRATEGIC PARALYSIS**
 - **KTO air defense suppression**
 - **Attack Iraqi forces in Kuwait & Republican Guards**
- **A “seamless” air campaign—no strict borders**

Figure 7. Planning the air war.

Inside out warfare

- **Military/civil leadership**
- **Key production**
- **Infrastructure**
- **Population**
- **Fielded military force**

Figure 8. Conceptual basis.

- I. **Disconnect Iraqi command structure (the “head”) from the military forces (the “fists” and “feet”) by targeting:**
 - **Internal control organizations (the “brain stem”)**
 - **Communications and electrical power (the “central nervous system”)**
 - **The transportation network and refined oil capacity (the “circulatory system”)**
- II. **Accomplish this while:**
 - **Minimizing losses of coalition aircraft and aircrews**
 - **Minimizing civilian casualties**
 - **Avoiding destruction of Iraq’s cultural, religious, and historic treasures**

Figure 9. Goals of the strategic air campaign.

LEADERSHIP	KEY PRODUCTION	INFRA-STRUCTURE	POPULATION	FIELDDED FORCE
Hussein regime	Electricity, oil	Only railroads	Psyops	Destroy strat air defense
• Incapacitate	• Only internal distribution and storage - not production, export capability	Added later: Bridges	• Iraqis	Destroy strat offense
Telecommunications and C3	– Nuclear biological chemical facilities		• Foreign workers	• Bombers
• Civil			• Soldiers in Kuwait	• Missiles
• Military	– Military research production/ and storage			Added later: Republican guards

Extract from original Air Campaign
concept briefing to Gen Schwarzkopf

Figure 10. Focus: what we would target.

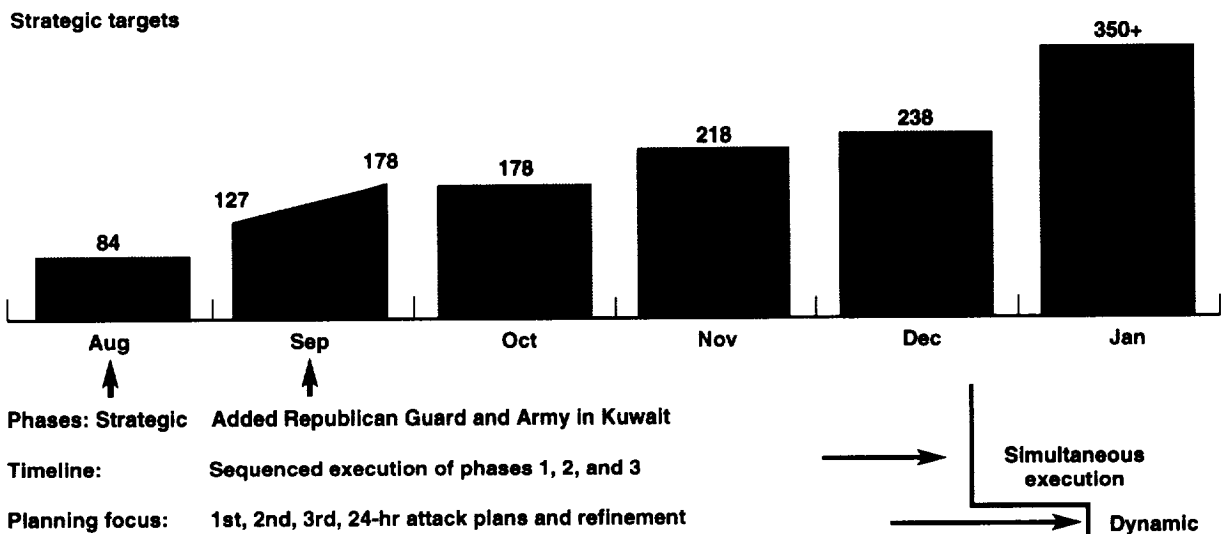


Figure 11. Evolution of the air campaign.

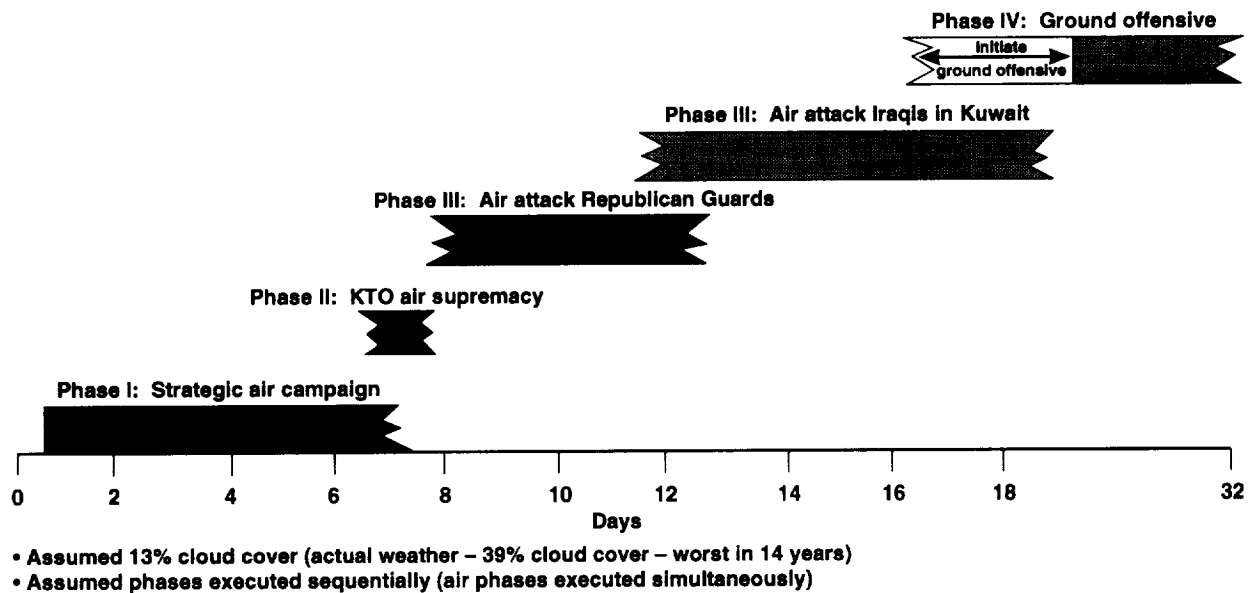


Figure 12. “Original” theater campaign.*

*As briefed to SECDEF 20 Dec 1990.

DIVISION	GAT (Guidance, Apportionment, Targeting)	ATO (Air Tasking Order)	ACE/OPS (Airborne Command Element/ Current Ops*)
PRODUCT	Iraq/Strategic Cell KTO cell • Master attack plan • Guidance letter • Target planning worksheets • Change sheets	• ATO (CAFMS) <ul style="list-style-type: none"> – Detail (callsigns, squaks, SPINs, etc.) – Airspace deconfliction – Tanker tracks • ATO transmission	• Execution management <ul style="list-style-type: none"> – Coordination – Immediate taskings – Changes
FOCUS	NEXT DAY	TOMORROW	TODAY *Current Ops separate Directorate
Example Activity on 1 Feb	PLANNING (3 FEB)	PROCESSING (2 FEB)	EXECUTION (1 FEB)

Three “wars” being worked each 24 hours

Figure 13. Organization: directorate for campaign plans.

Country	Ftr/Atk	Tanker	Airlift	Other	Total	Percent of force
United States	1,323	285	175	207	1,990	76.1
Saudi Arabia	276	15	38	10	339	12.9
Grt. Britain	57	9	3	4	73	2.8
France	44	3	12	7	66	2.5
Kuwait	40	---	3	---	43	1.6
Canada	26	---	---	2	28	1.1
Bahrain	24	---	---	---	24	.9
Qatar	20	---	---	---	20	.8
UAE	20	---	---	---	20	.8
Italy	8	---	---	---	8	.3
New Zealand	---	---	3	---	3	1
TOTALS*	1,838	312	234	230	2,614	99.9

*Total does not equal 100% due to rounding

Figure 14. Coalition air strength on eve of war.

- I. **The war opened with three strikes:**
 - 1) **Task force Normandy (AH-64 Apache + HH-53 Pave Low)**
 - **Iraqi radar vans on western Iraqi-Saudi border**
 - 2) **F-117 Stealth fighters**
 - **Hardened air defense sites and strategic targets**
 - 3) **TLAM cruise missiles**
 - **“Soft” targets**
- II. **Conventional attackers followed**
- III. **Operational intensity:**
 - **400 strikers in first 4 hr**
 - **668 strikers total in first night**
 - 530 USAF(79%)**
 - 90 USN/USMC(13%)**
 - 24 RAF(4%)**
 - 12 RSAF(2%)**
 - 12 FAF(2%)**

Figure 15. The air war: the first night.

The F-117:

- **Was the only coalition weapon capable of hitting hardened targets in extremely high-threat areas.**
- **Constituted less than 2.5% of coalition strike aircraft, but hit 31% of strategic Iraqi targets attacked on first day**
- **Flew only 2 % of Gulf War strike sorties, but flew against 40% of all Iraqi strategic targets**
- **Had high leverage**
 - **At same time 8 conventional strike airplanes escorted by 30 electronic warfare, Wild Weasel, and air defense suppressors were attacking 1 airfield, 21 F-117s were attacking 37 even more heavily protected targets by themselves**

Figure 16. The air war: the impact of stealth.

- **Total U.S. munitions (smart and dumb) expended:** **84,200 tons**
 - USAF expended 60,624 tons (72%)
 - USN/USMC expended 23,576 tons (28%)
- **Total smart munitions expended:** **7,400 tons**
 - USAF expended 6,660 tons (90%)
 - 30% of AF total dropped by F-117
 - USN/USMC expended 740 tons (10%)
- **Total dumb munitions expended:** **76,800 tons**
 - USAF expended 53,964 tons (70%)
 - 47% of AF total dropped by B-52
 - USN/USMC expended 22,836 tons (30%)

Figure 17. The air war: U.S. weapon utilization.

- **Approximately 19,800 precision munitions were expended in the war**
- **Percentage breakdown by type was:**

Paveway LGB (GBU-10/12/16/24/27/28)	46.7%
Mavericks (AGM-65B/D/G)	27.8%
Hellfires	13.7%
HARMS	9.1%
Tomahawks	1.5%
Misc. (Walleye, GBU-15, Skipper, SLAM)	1.1%

Figure 18. The air war: smart weapon utilization.

<u>War</u>	<u>Tonnage</u>	<u>Length, months</u>	<u>Tonnage/ month</u>
WWI	137.5	8	17.19
WWII	2,150,000	45	47,777.78
Korea	454,000	37	12,270.27
Vietnam/SEA	6,162,000	140	44,014.29
Gulf War	60,624	1.5	40,416.00

Gulf war tonnage is only 11% of that dropped on Japan (537,000 tons), and less than 4% of that dropped on Nazi Germany (1,613,000 tons).

Figure 19. The air war: level of intensity & effort (USAS/USAAF/USAF bomb tonnage statistics).

- Precision weapons offset mass, reducing sortie requirements
- Precision weapons offer unprecedented accuracy; bomb CEPs have declined from 3,300 ft in WWII to less than 10 ft now
- Precision weapons offer virtually “one weapon–one kill” expectations against any pinpoint target—particularly tanks
- Precision strikes can achieve nuclear-equivalent effects with conventional munitions
- Precision weapons minimize collateral damage and civilian casualties
- The synergy of airlift, stealth, and PGMs has created a new level of military air power effectiveness

Figure 20. The air war: the impact of precision.

1. **Strikes in Baghdad area drove Hussein regime underground in disorientation, confusion, and ignorance**
 - Leadership had to rely on CNN to know what was happening
2. **Strikes across the country shut down the Iraqi electrical power grid**
 - TLAMS and 200 sorties of manned aircraft returned Iraq to the pre-Edison era
3. **Strikes targeting fuel and lubricants sapped the lifeblood of the Iraqi military machine**
 - 1,200 tons of bombs dropped in 500 sorties accomplished more than 185,841 tons of bombs dropped in 50,000 sorties in WW-2 against Nazi oil facilities
4. **Strikes across Iraq and Kuwait achieved clear cut interdiction**
 - 41 of 54 bridges dropped, and 32 pontoon bridges destroyed
5. **Strikes destroyed the Iraqi Air Force aloft and in its shelters**
 - IQAF attempts to “ride out” air campaign failed; “shelter busting” caused IQAF to “flush” to Iran

Figure 21. What the air war accomplished.

- USAF lost 14 aircraft
- Prewar estimates had forecast a total of 50 to 80 coalition losses
- Losses low because of planning, training, targeting, and tactics
- Prewar estimates ranged from .5% (.005 losses/sortie) to possibly 3% (.030 losses/sortie). Some pessimists suggested 10% (.10 losses/sortie)
- Actual loss rate was .047% (.00047 losses/sortie)
- The Gulf War in the context of USAS/USAAF/USAF losses in previous wars:

<u>War</u>	<u>Combat sorties</u>	<u>Losses</u>	<u>Losses/sortie</u>	<u>Percent</u>
World War I	28,000	289	.010	1.0
World War II	1,746,568	18,369	.010	1.0
Korea	341,269	605	.0017	.17
Vietnam	1,992,000	1,606	.00081	.081
Gulf War	29,393	14	.00047	.047

Figure 22. The air war: USAF losses.

- **Modern, high-technology aerospace systems had sustained mission capability rates of approximately 90%**
 - Appears to be new “baseline” standard
 - Not just a “surge” phenomena
 - True for entire coalition
 - True for aircraft, missiles, helicopters, and electronics
 - Countered “simpler, cheaper” argument of 1980’s defense reformers
- **Peacetime and wartime mission capability percentage data for Air Force chosen because of availability; other services & allies similar:**

<u>Aircraft</u>	<u>Peacetime</u>	<u>Gulf War</u>
A-10	90.4	95.5
C-5	69.0	78.0
C-130	78.0	84.0
C-141	80.0	86.0
F-4G	83.7	88.7
F-15C/D	85.1	93.7
F-15E	80.4	95.5
F-16	90.2	95.4
F-117	81.6	85.8
KC-10	95.0	95.0
KC-135	86.0	89.0

Figure 23. The air war: reliability & maintainability issues.

- **Destroying Iraqi armor and artillery established as a key priority by CENTCOM Commander General Schwarzkopf**
- **Four weapon combinations proved particularly deadly:**
 1. **F-111 + Pave Tack FLIR Turret + GBU-12 500 lb LGB**
(up to 150 armor kills per night)
 2. **F-15E + LANTIRN targeting & navigation pods + GBU-12**
(2 F-15Es destroyed 16 tanks for expenditure of 16 GBU-12s)
 3. **A-10 + AGM-65D Maverick imaging infrared (IIR) missile**
(Maverick gave “one missile—one kill” results against T-72)
 4. **AH-64 + FLIR/LLTV/Helmet-mounted sight + Hellfire missile**
(one Apache unit scored 102 hits for expenditure of 107 missiles, a hit rate of 95%)
- **Bottom line: aircraft & helicopters are now the MOST EFFECTIVE antitank weapon**

Figure 24. The air war: the anti-armor/artillery campaign.

- **Air attack did not “prepare” the battlefield, it DESTROYED it**
- **Gulf War reaffirmed that air attack has a powerful psychological impact upon troop morale**
 - **35,000+ attack sorties targeted Iraqi army**
 - **5,600 of these targeted the Republican Guard**
 - **Between 20% and 40% of Iraqi troops deserted prior to G-Day**
- **Full range of coalition aircraft struck at Iraqi Army, day and night**
 - **From day one, B-52s attacked every three hours**
 - **Were most feared attacker**
 - **The 249 F-16s in Gulf flew 13,500 sorties, more than any other strike airplane**
 - **Used as “killer scouts” and “killer bees”**

Quotable quotes:

Q: “Why did you surrender?” A: “It was the AIRPLANES!”

“None of my troops would get near a tank at night because they just kept blowing up.”

Figure 25. The air war and the Iraqi army in Kuwait.

- **C-130 theater airlift was critical to the success of the “Hall Mary” maneuver**
 - **Flew 1,200 missions, with 10-minute separation between planes**
 - **Delivered 14,000 people**
 - **Delivered 9,000 tons of equipment**
 - **Flew fuel & general cargo for the army’s XVIII corps into logistics base Charlie, on the Trans-Arabian pipeline & (tapline) road**
- **When G-Day commenced, coalition air attack obviated any need for bitter and prolonged ground combat**
- **Could not be characterized as “airland battle” as defined in FM 100-5**
- **On night of G + 2, JSTARS detected Iraqi III corps bugging out, setting the stage for the “highway of death” air strikes on Feb 26–27**

Figure 26. The air war and the ground operation.

- **E-3B AWACS (Airborne Warning And Control System)**
 - Proved critical to success of air campaign
 - Identified threats
 - Prevented “Blue on Blue” fire
 - Managed air traffic control for Gulf War—up to 3,000 sorties per day
- **E-8A JSTARS (Joint Surveillance Target Attack Radar System)**
 - An “AWACS” for the ground war
 - Identified threats, including armor & SCUD tels
 - Provided “real-time” targeting to strike aircraft
 - Responsible for success at Khafji & “highway to death”
- **TDF (Tactical Digital Facsimile)**
 - “Today’s telephone to the modern battlefield commander”
 - Operated at temperature up to 125 °F & blowing sand
 - In opening weeks was only secure means of updating key information short of having a flying courier service
- **Space-based systems**
 - Gulf War the first “space-supported war”
 - NAVSTAR Global Positioning System (GPS)
 - Defense Meteorological Support Program (DMSP)
 - Defense Satellite Communications System (DSCS)

Figure 27. The air war: C³ issues.

Intelligence and bomb damage assessment

- The single most controversial issue in entire air campaign
- Accuracy critical to determination of when to launch G-Day
- Estimates varied widely on levels of destruction
- CENTAF forced to rely on strike video as most reliable indicator of true destruction

SCUD detection and destruction

- Anti-SCUD air campaign involved 2,493 sorties against two major “SCUD boxes”
- Combination of air action and ground-based special operating forces proved very productive
- Air campaign reduced SCUD launches from 5/day at beginning of war to 1/day to end of war
- Air campaign degraded SCUD accuracy by forcing launches “on the run”
- BUT “shoot and scoot” SCUDs posed difficult challenge, and were never completely neutralized

Figure 28. The air war: areas of concern.

	<u>V-2</u>	<u>SCUD</u>
Number launched	1,190	91
Daily average	6	2
Number/percentage reaching target	517/43%	48/53%
Number engaged by defenses	(n/a)	47
Number intercepted	(n/a)	45
Casualties—wounded	6,500	450
Casualties—killed	2,700	42
Combined killed/injured per missile	18	11
Wounded per missile	13	10
Killed per missile	5	1
Ratio of wounded to killed	3:1	10:1
Damaged/destroyed buildings/homes	123,000	10,750
Damaged/destroyed buildings/homes per missile	238	224

Figure 29. Comparison of SCUD with V-2 Anti-London Campaign.

Friendly fire

- Air-to-ground friendly fire incidents claimed 15 Americans killed and 11 wounded
- Not exclusively an “air” problem
 - Ground vs. ground incidents were over twice as numerous (2.14:1) resulting in 24 deaths and 58 woundings
- Will demand intensive work on ID technologies

Combat search and rescue (CSAR)

- Too few aircraft available to meet both CSAR & SOF needs
- Seven CSAR missions launched
 - 3 were successful
 - Only 3 of 64 downed aircrew picked up (4.7%)
- Clear need for fast, responsive, & survivable CSAR systems

Figure 30. The air war: areas of concern (cont).

"The United States relies on the Air Force and the Air Force has never been the decisive factor in the history of wars"

– Saddam Hussein, Aug. 1990

"Gulf lesson one is the value of air power"

– President George Bush, May 29, 1991

"The air campaign was decisive"

– Secretary of Defense Dick Cheney, Apr. 14, 1991

"Air power is the decisive arm so far, and I expect it will be the decisive arm into the end of the campaign, even if ground forces and amphibious forces are added to the equation...If anything, I expect air power to be even more decisive in the days and weeks ahead"

– JCS Chairman Gen. Colin Powell, Feb. 21, 1991

"The day we executed the air campaign, I said "we gotcha!"

– Gen. Norman Schwarzkopf, July 3, 1991

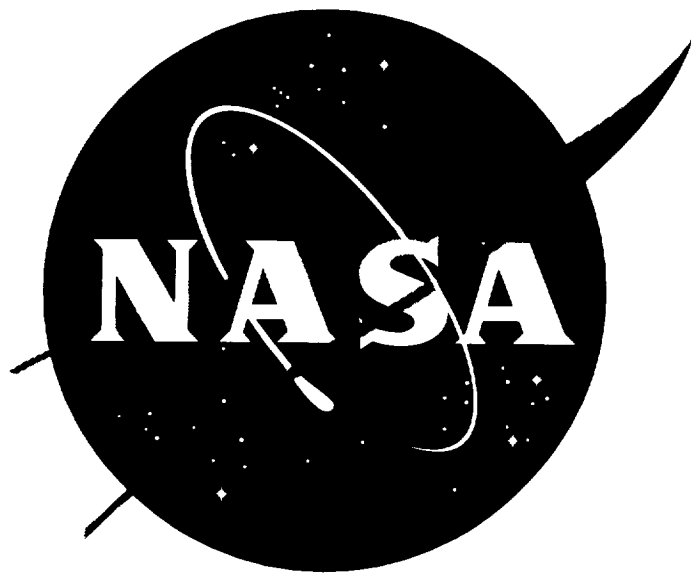
"The Gulf War marked the apotheosis of twentieth century air power"

– Air Vice Marshal R.A. "Tony" Mason, RAF (Ret)

"The Iraqi military machine folded under the pressure of allied smart bombs and air power"

– Harry Smith, CBS News, Aug. 2, 1991

Figure 31. The air war: selected quotes.



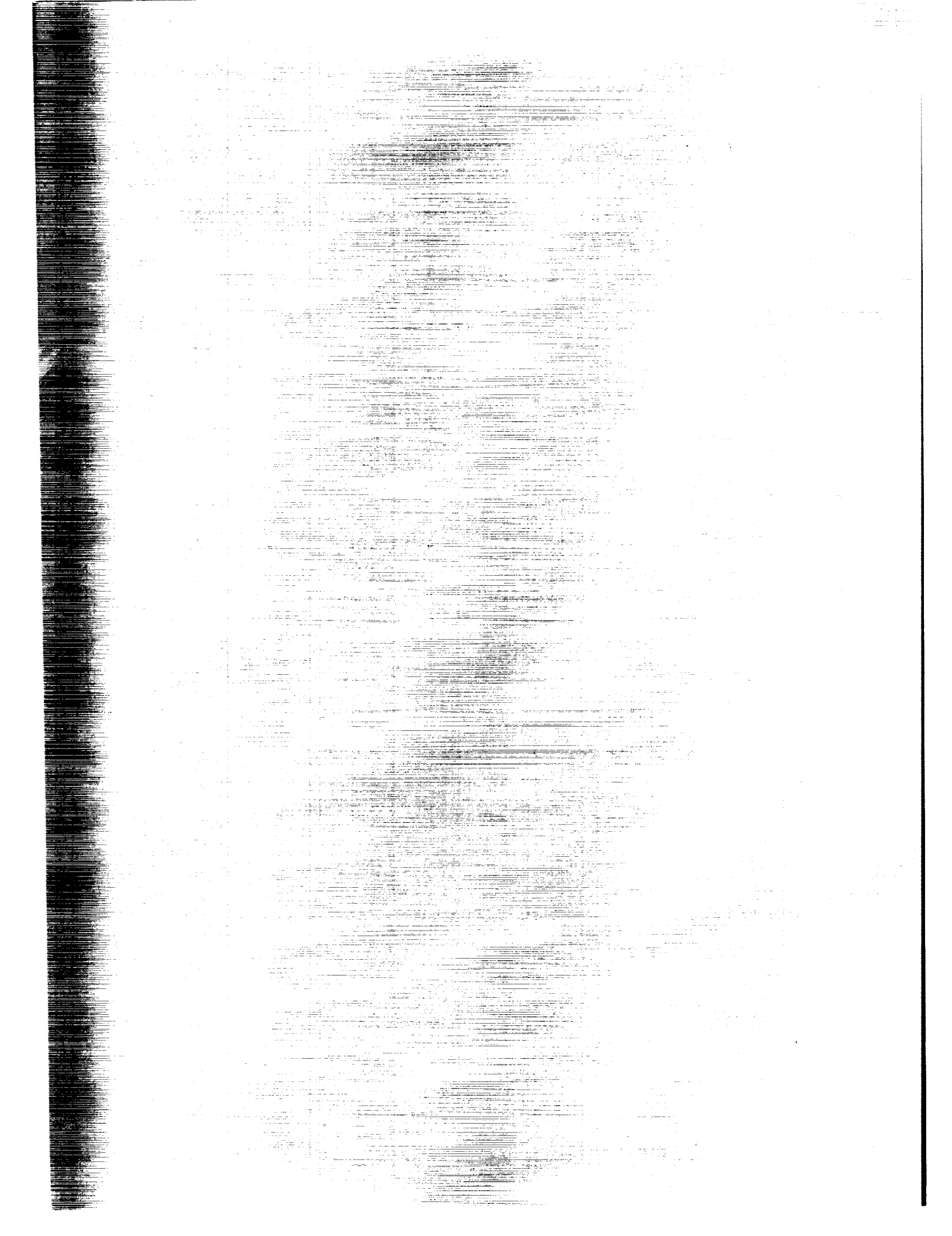
NOMENCLATURE

AA	associate administrator
A/C	aircraft
ACE/OPS	airborne command element/current ops
AFFTC	Air Force Flight Test Center, Edwards, CA
AFTI	Advanced Fighter Technology Integration
AIA	Aerospace Industries Association
AIAA	American Institute of Aeronautics and Astronautics
AR	analytical redundancy
ASEB	Aeronautics and Space Engineering Board
ATO	air tasking order
AWACS	airborne warning and control system
CADRE	Cooperative Advanced Digital Research Experiment
CFD	computational fluid dynamics
CID	controlled impact demonstration
CSAR	combat search and rescue
CTF	combined test force
DEM/VAL	demonstration/evaluation
DFBW	digital fly-by-wire
DFRF	Dryden Flight Research Facility, Edwards, CA
DMSP	defense meteorological support program
DOD	Department of Defense
DSCS	defense satellite communications system
E&D	evaluation & demonstration
ELAC	elevator & aileron computers
EMD	engineering and manufacturing development
EMI	electromagnetic interference
FAA	Federal Aviation Administration
FDIR	frequency domain identification routines
FMEA	failure modes and effects analysis
FNG	fresh new guy/greenhorn

<i>g</i>	acceleration of gravity
GAT	guidance, apportionment, targeting
GD	General Dynamics (corporation)
GE	General Electric (company)
GNAC	guidance, navigation, and control
GPS	global positioning system
HIRF	high-intensity radio frequency (radiation)
HTTB	high-technology test bed
IIR	imaging infrared
IMU	inertial measurement unit
ITF	Integrated Test Facility
JAA	Joint Airworthiness Authority
JOVIAL	USAF version of computer algorithmic language ALGOL 58
JSTARS	joint surveillance target attack radar system
LTV	Ling Temco Vought Corporation, Grand Prairie, TX
<i>M</i>	Mach number
MTBF	mean time between failures
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NCO	non-commissioned officer
OAST	Office of Aeronautics and Space Technology
OART	Office of Advanced Research and Technology
PI	principal investigator
PIO	pilot-induced oscillation
PRC	Planning Research Corporation
R&D	Research & Development
RAE	Royal Aircraft Establishment
REBUS	resident backup software
RM	redundancy management
RPV	remotely piloted vehicle
SAS	stability augmentation system
SCA	Shuttle Carrier Aircraft
SCW	Supercritical Wing

SEC	spoiler and elevator computer
SITE	Simulated Integrated Test Environment
<i>T,t</i>	time
TACT	Transonic Aircraft Technology Program
TDF	tactical digital facsimile
TO	technical order
TQM	Total Quality Management
USAF	United States Air Force
V&V	verification & validation
VTOL	vertical takeoff and landing

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